Peer review status:

This is a U.S. Geological Survey peer-reviewed preprint submitted to EarthArXiv. It has also been submitted to the Journal of American Water Resources Association as a journal article

This information product has been peer reviewed and approved for publication as a preprint by the U.S. Geological Survey

Seasonal Estimates of Instream Nitrogen & Phosphorus Loads from New England Watersheds Discharging to Long Island Sound, 2000-2020

By Richard B. Moore, Richard A. Smith, Laura Hayes, Jennifer S. Stanton, and Craig J. Brown

U.S. Geological Survey (Moore), Pembroke, New Hampshire, USA; U.S. Geological Survey (Stanton), Northborough, Massachusetts, USA; Geological Survey retired (Smith, Hayes, Brown), (Correspondence to Moore: rmoore@usgs.gov).

Key words: nitrogen, phosphorous, loads, Long Island Sound, dynamic, seasonal, SPARROW, model

This paper demonstrates the capability and utility of seasonal time steps in a SPAtially Referenced Regression On Watershed attributes (SPARROW) model of nutrients in streams and rivers. Also included in the models is the capability of testing for and including a storage component of nutrients that remain from one season to the next. Two additional newly available attributes are also included, a term representing the spring snowmelt nutrient contributions to the rivers, and another term representing the seasonal groundwater contribution of nitrogen to the streams and rivers.

Abstract

Seasonally dynamic estimates of total nitrogen and total phosphorus loads delivered to Long Island Sound from New England watersheds are estimated by use of seasonally dynamic SPARROW (SPAtially Referenced Regression On Watershed attributes) models. These models are part of the larger Long Island Sound Study (LISS) a coordinated effort by the U.S. Environmental Protection Agency (EPA), the States of New York, Connecticut, and other New England States, and communities within the region, with the common goal of protecting and restoring the health of the aquatic environment of Long Island Sound. The models aid the LISS goals by improving the understanding of the sources, transport, and delivery of nutrients from New England watersheds southward to Long Island Sound. Seasonal estimates provide better information for management. These estimates advance our understanding of loads, indicate seasonal processes, and include ranges, extremes, and lags in the system from one season to the next.

Dynamic models allow seasonal loads to vary substantially season-to-season and year-to-year. The SPARROW models for this study use both dependent variables (the nutrients) and

predictor variables that vary seasonally throughout 21 years, from 2000 through 2020. Significant source pathways in this framework, with probability levels (p-values) less than 0.05, include seasonally dynamic pathways such as atmospheric deposition, spring snowmelt, and groundwater input of nitrogen.

INTRODUCTION

Long Island Sound has long faced issues of excess upstream nutrient pollution resulting in eutrophication and even hypoxia within the Sound or within its tributary embayments. As such, the Long Island Sound Partnership and the implementation, in 2000, of a Total Maximum Daily Load (TMDL) plan (New York State Department of Environmental Conservation and Connecticut Department of Environmental Protection, 2000), has resulted in the reduction of nutrients to the Sound (Long Island Sound Partnership, 2026; New England Interstate Water Pollution Control Commission, 2026). To continue the effort, and to monitor its effectiveness, water quality conditions throughout the Long Island Sound watershed are routinely sampled for nutrients such as total nitrogen and total phosphorus. With this sampling information as its foundation, estimates of the transient nutrient loads to the Sound from specific upstream source pathways are sought.

Developing estimates of nutrient loads and their sources delivered from the Long Island Sound watershed is an important part of the plan for restoring the quality of the Sound, because these estimates provide references from which management goals can be targeted and evaluated. SPAtially Referenced Regression On Watershed attributes (SPARROW) models can be used to develop these estimates (Schwarz and others, 2006). A deterministic watershed model called Hydrologic Simulation Program – Fortran (HSPF) (U.S. Environmental Protection Agency, 2021a) is also used in the Long Island Sound Study (LISS). Joint use of SPARROW and HSPF allows the models to inform each other, enhancing the robustness of subsequent modeling efforts.

The dynamic seasonal SPARROW models for nitrogen and phosphorus, presented here, enable scenario testing for Long Island Sound. These models provide a framework for testing various scenarios, where changes in loads to the Sound can be predicted as a response to potential changes in the magnitude of various predictors, especially source, variables. Scenario testing has already been accomplished based on steady state SPARROW models (Detenbeck and others, 2018, Chamberlin and others, 2022). The new models presented here provide seasonally dynamic frameworks for scenario testing.

SPARROW models focus on spatial details of individual catchments and accumulate their processes from headwater to river mouth, and the model coefficients that quantify nutrient sources and pathways are statistically determined from the input data during the model calibration process. Most previous SPARROW models, done for areas in New England, or elsewhere, have not incorporated temporal changes in conditions due, in part, to limited availability of dynamic data needed as model input. The SPARROW modeling process, for average (steady state) conditions, is described in Smith and others (1997), Schwarz and others (2006), and specifically for New England or the Northeast, by Moore and others (2004 and 2011), and Ator (2019). A semi transient model for the Northeast, generating mean predictions for each of the four seasons, was developed by Schmadel and others (2021). Schmadel and others (2024) developed fully dynamic representation in the Illinois River Basin to generate season-specific predictions for each year in a series of years.

To our knowledge, the model described in this study is the first published seasonally dynamic regional SPARROW model developed for a major watershed within the Northeastern United States. Using this dynamic seasonal approach, estimates cover the variations over 21 years or 84 seasonal time steps from 2000 through 2020. These results can be examined to see how conditions have varied with time on a seasonal basis and how these varying conditions affected loads to Long Island Sound and its tributaries and embayments. These results can help identify the timing and conditions when input loads can lead to eutrophication or hypoxia; therefore, these results support targeted mitigation efforts to avoid problem conditions in the future by identifying source shares and delivery fractions.

Seasonally dynamic estimates of total nitrogen and total phosphorous are modeled for the entire watershed north of Long Island Sound (LIS) (figure 1). Within these New England watersheds, stream loads of total nitrogen and total phosphorus at monitoring stations are the dependent variables, and are estimated at unmonitored locations by using measured predictor attributes which change spatially and temporally throughout the basin. This study aids in the LISS effort by quantifying dynamic sources, their drivers, and their delivery fractions.

The modeled area includes the watersheds that drain 41,708 km^2 southward from New England into Long Island Sound (figure 1). All six New England States (Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and even a small portion of Maine) and New York have areas that drain to Long Island Sound. The four largest river watersheds draining this area include the Connecticut, Housatonic, Thames, and Pawcatuck Rivers. The Connecticut River watershed is the largest watershed by a substantial margin and extends about 300 miles northward into Canada (figure 1). Seasonally dynamic estimates of total nitrogen and total phosphorous are modeled for this entire watershed.

Figure 1. Modeled areas include the watersheds draining to Long Island Sound from the north. These include the Housatonic, Connecticut, Thames, and Pawcatuck River watersheds and smaller watersheds that drain directly to Long Island Sound.

METHODS

The Stream Network

The first requirement in creating a dynamic SPARROW model is the development of a digital representation of the stream and waterbody network. For the digital stream network, we used NHDPlusV2.1 (McKay and others, 2012). NHDPlusV2 is a network commonly used for SPARROW modeling, along with a set of modified routing attributes used for SPARROW modeling (Schwarz, 2019, Brakebill and others, 2020). In this network, reaches are depicted as lines (or flowlines). Water bodies are depicted as polygons, and the catchment areas draining directly to network segments are depicted as polygons. The goal in creating the model is to include estimates of nitrogen loads, phosphorus loads, source contributions (and confidence intervals) for all 20,977 network flowlines within the stream network for each seasonal timestep.

In developing a dynamic seasonal model, this stream network gets replicated for each seasonal timestep, with each replication representing a given season and year combination (in this case 21 years x 4 seasons per year, for a total of 84 timesteps). The dependent and predictor data are then assigned to the appropriate reach and time step within the input dataset. Because much of the predictor data are available by month, the monthly data were aggregated into seasons where: January, February, and March = winter; April, May, and June = spring; July August and September = summer; and October, November, and December = fall.

Dependent Variables – what we are predicting

The dependent variables in the models are seasonal loads of total nitrogen (N) (figure 2) and total phosphorus (P) (figure 3) calculated using river flows and N and P concentrations measured at streamgages. Streamflow and N and P concentration data were downloaded from the U.S. Geological Survey (USGS) Water Data for the Nation (WDFN; U.S. Geological Survey, 2025) which includes the existing, extensive state and federal streamflow and water-quality data necessary for SPARROW modeling. Loads were calculated using Weighted Regressions on Time, Discharge, and Season (WRTDS) (Hirsch and others, 2010) or Fluxmaster software (Schwarz and others, 2006; Lee and others, 2016) depending on monitoring data availability. A total of 45 monitoring sites had adequate data to compute N loads (figure 2), and 37 sites had adequate data to compute P loads (figure 3). WRTDS typically requires 100 or more samples spread out over years and can adjust for short term trends. Fluxmaster requires less data and can be used to obtain greater spatial coverage and represent a wider array of predictor watershed characteristics. Fluxmaster was used in this investigation for obtaining load data for the northern part of the study area. Both approaches assume that flow and concentration are related and that there can be a trend in that relation over time. The main distinction between the two techniques is that Fluxmaster incorporates a single trend over the modeled timeframe, while WRTDS can adjust for shorter-term trends by changing over the timeframe, which is why more samples are needed.

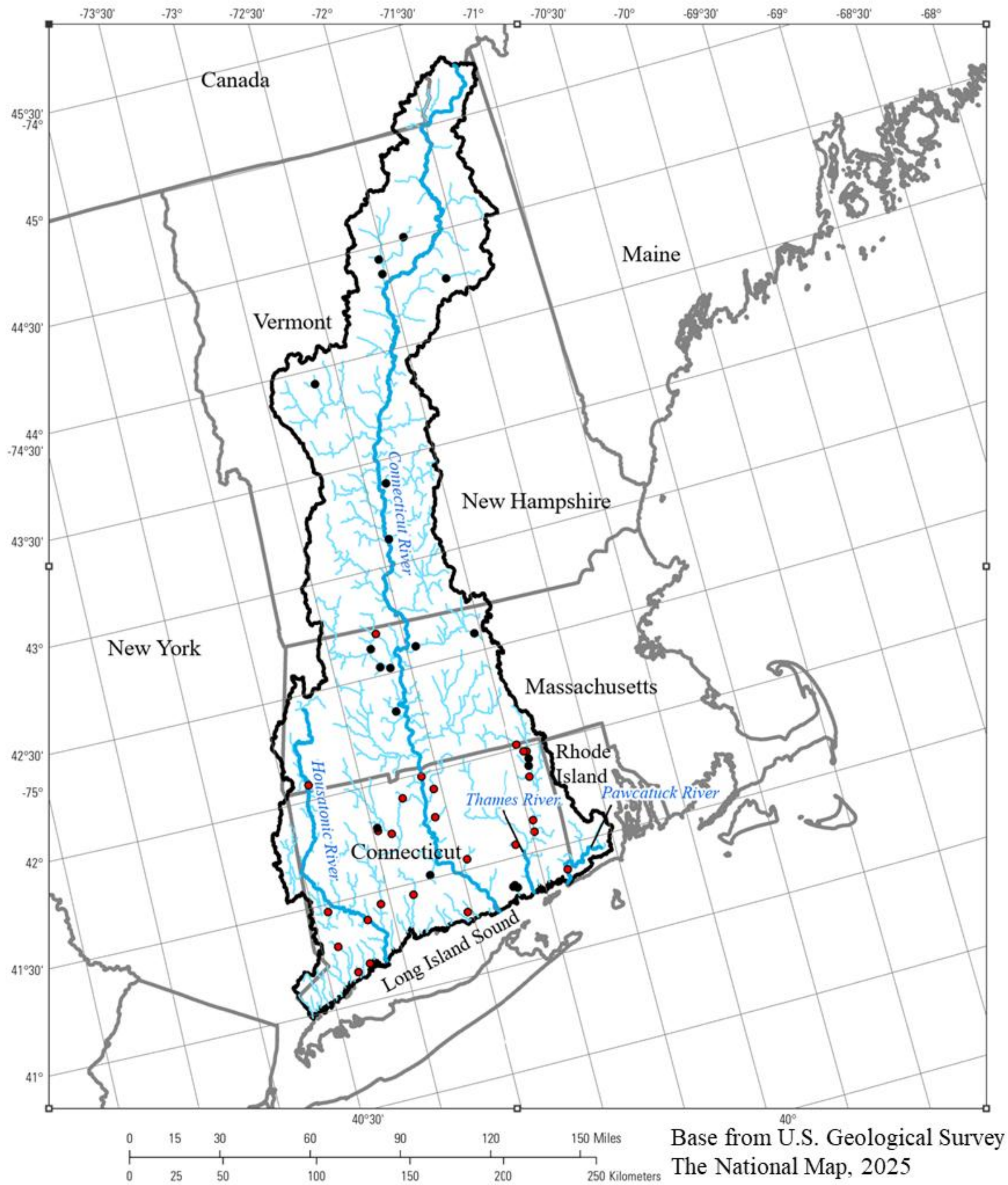

Figure 2. Nitrogen load monitoring sites: Red dots represent sites where the Weighted Regressions on Time, Discharge, and Season (WRTDS) software has been applied to estimate seasonal nitrogen loads at 25 sites. Black dots represent sites where Fluxmaster has been used to estimate nitrogen loads at 20 additional sites.

Figure 3. Phosphorus load monitoring sites: Red dots represent sites where WRTDS software has been applied to estimate seasonal phosphorous loads at 28 sites. Black dots represent sites where Fluxmaster has been applied to estimate phosphorous loads at 9 additional sites.

Nutrient Source Variables

Predictor datasets are spatially distributed, assigned to each catchment, and seasonally discretized for predictors that change with time. These predictors include N or P source variables to represent point sources from wastewater treatment plant discharges, atmospheric deposition, snow cover, population on septic, agricultural sources, and non-agricultural fertilizer. A new variable, Baseflow N (BFN), quantifying base flow groundwater nitrogen loads was also evaluated and included in model estimates. Some predictors, such as urban lands, are assigned for each catchment and timestep but change more gradually over years rather than seasonally.

Wastewater Discharge

Wastewater Treatment Plant (WWTP) point source discharges are from municipal wastewater discharge facilities that treat municipal waste and sewage. Data were developed using National Pollutant Discharge Elimination System NPDES data (Skinner and others, 2024). Wastewater treatment plants are point sources of N and P and are quantified as seasonal loads in kilograms/season (kg/season) discharged directly into the surface water network.

Atmospheric Deposition

Atmospheric deposition of N occurs in both wet and dry forms, is spatially distributed, and varies with time (Figure 4). The model captures this source by including the spatially distributed estimates of TN modeled using EPA's Community Multiscale Air Quality (CMAQ) modeling results. To improve our understanding and better quantify phosphorous transport within the Long Island Sound and other watersheds, atmospheric deposition of phosphorous should be measured and mapped on a periodic (at least monthly or seasonal) basis.

CMAQ is a suite of programs for conducting air quality model simulations (U.S. Environmental Protection Agency, 2021b and 2025a), which builds upon data from the National

Atmospheric Deposition Program (NADP, 2023). The CMAQ data are available in monthly rasters with 12 km cell sized resolution. The monthly rasters were summed to seasonal totals and then allocated to the catchments by area overlap.

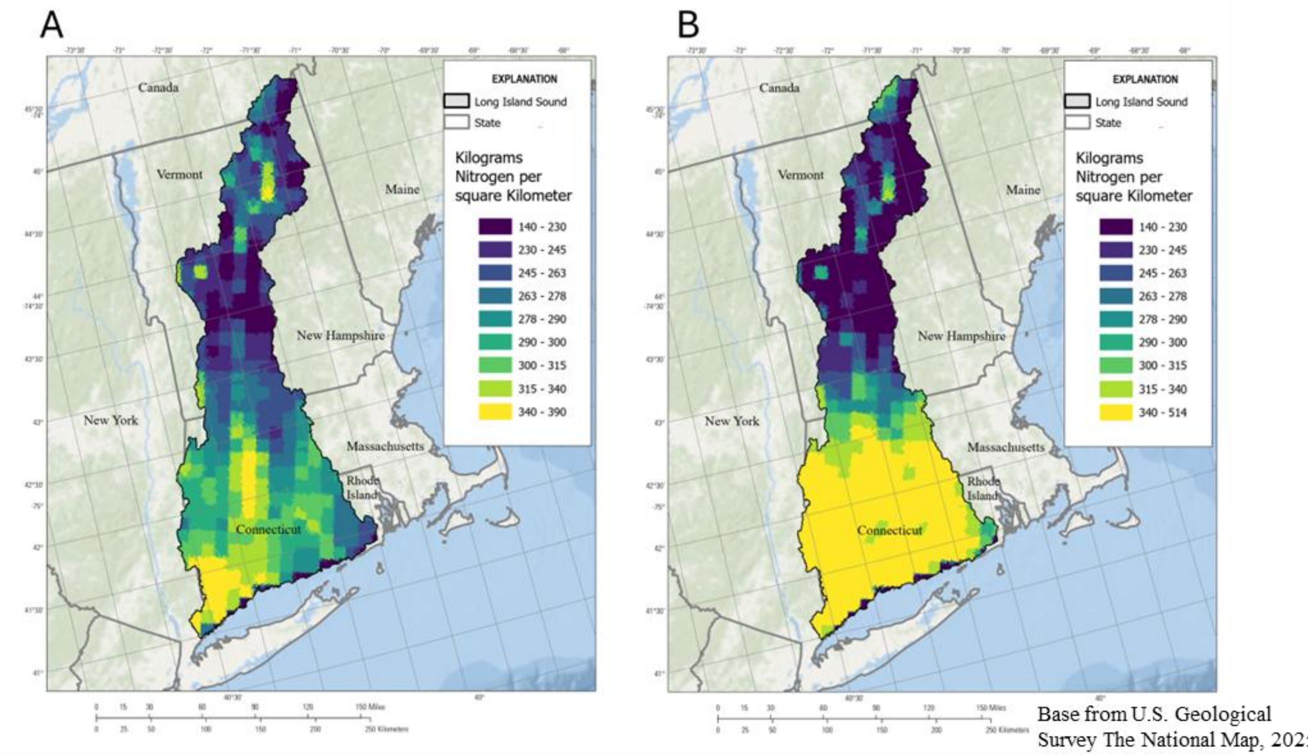

Figure 4. Atmospheric deposition of nitrogen in kilograms per square kilometer. Examples are for A) Spring 2011 and B) Summer 2011; showing variation in deposition from one season to the next.

Snow Cover

Average seasonal snow-cover area within each catchment was tested and used as a predictor variable. Nutrients are stored in the snow and get mobilized during the spring melt. In New England, the snow typically melts by the end of spring. In areas with deeper snow, the snow persists longer, which increases the ***average*** spring seasonal snow-cover area and leads to increased nutrient loads during spring snow melt.

To adjust for cloud cover, snow percentages from the visible data (without cloud cover) were prorated to the entire catchment area and then averaged by catchment for each season. MODerate-resolution Imaging Spectroradiometer (MODIS) data are produced by the National Aeronautics and Space Administration (NASA) from satellite images and are used to estimate snowcover (Hall and others, 2006). The data come in individual raster images at 500-m cell-size resolution, for each 8-day temporal resolution, covering our SPARROW modeling period of 2000–2020. Images show areas of snow, no snow, and areas of no data (i.e., covered by clouds). The data were processed by iterating through each 8-day period and allocating the data to seasons across the 21-year record. Eight-day periods were prorated when they spanned multiple seasons. Results, based on cell counts, show the snow cover, cloud cover, and no-snow areas for each catchment for each of the 84 seasonal time steps.

National Land Cover Data

The National Land Cover Database (NLCD) for the United States is produced by the USGS in association with the Multi-Resolution Land Characteristics (MRLC) Consortium (U.S. Geological Survey, EROS Center, 2018, Dewitz, 2023, MRLC Consortium, 2021). The NLCD includes a standard land cover product suite that provides 16 land cover classes for the conterminous United States and Alaska, including, for example, high intensity and medium intensity developed lands which were grouped together and tested in both the N and P models. Other grouped categories tested included an agricultural lands grouping and a forested lands grouping. The areas of the various land cover categories were assigned to each catchment (figure 5). Years for which the data were available include 2019, 2001, 2004, 2006, 2008, 2011, 2013, 2016, and 2019 (Wieczorek and others, 2022a and 2023)   Land uses during the missing years were approximated using the land use data of the closest year (or for ties, one of the two closest years).

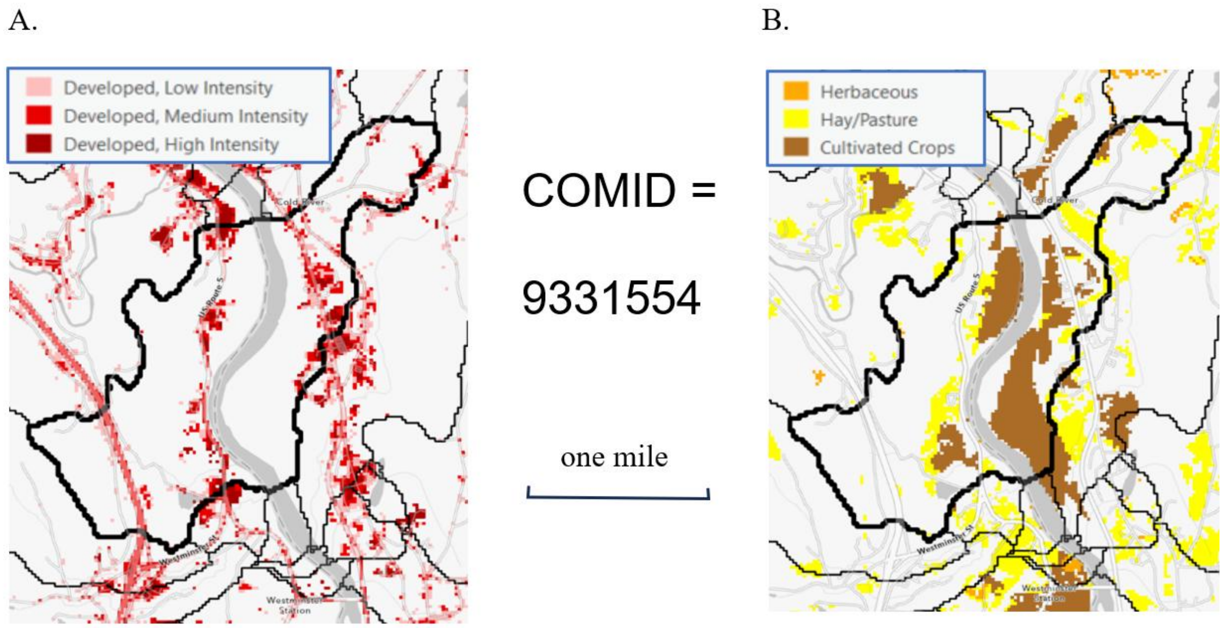

Figure 5. Example of a NHDPlusV2 catchment, outlined with bold black line, associated with a flowline (identifying NHDPlus catchment ID, COMID, = 9331554) along the Connecticut River and associated urban developed land (A) (12% of the catchment area) and agricultural land (B) (27%) land cover categories that are within the catchment and are allocated to the catchment in the model.

Onsite Septic Disposal

The estimated population within each catchment with on-site septic disposal was estimated by a three-step process as follows:

1. The population identified by the 2010 US census are more accurately located. This is done by US Environmental Protection Agency (USEPA) using a technique called dasymetric mapping (2025b). Datasets of population counts from 2010 and 2020 census blocks (original data on human population collected by the U.S. Census Bureau, U.S. Department of Commerce) are reallocated by USEPA within those blocks based on 30m pixel resolution land cover and land use data. Urban cells, for example, within a census

block receive a greater proportion of the population, while uninhabited areas such as airports, swamps, parks, and highways will not receive any population. Having a more accurately located population makes allocating that population to catchments more accurate.

2. The population serviced by municipal sewer systems was excluded. The excluded population was estimated by using geographically referenced datasets of sewer lines provided provisionally (unpublished data subject to review) by states, counties and municipalities. Agencies that are developing data, on connected sewer service areas, include the Connecticut Department of Energy & Environmental Protection, the Massachusetts Department of Environmental Protection, the New Hampshire Department of Environmental Services; and the Vermont Agency of Natural Resources in partnership with the University of Vermont and its students. Distances to sewer lines were buffered by 300 m, and the population count from within the buffered areas was excluded.
3. The remaining population outside of the buffer zones was assumed to require on-site septic disposal and was allocated to the catchments. This population with on-site septic disposal was tested as a model input but was not a significant predictor; therefore, the variable was not pursued further for this investigation.

Agricultural Applications of Fertilizer and Manure

County- and state-based estimates of the nitrogen and phosphorus contents of fertilizers applied to agricultural lands and from livestock manure waste were tested and used as predictors. Source loadings for each catchment were determined from county-level application rates of fertilizer and manure that were spatially distributed based on agricultural land cover NLCD categories and were then allocated to the catchments for each time step (Falcone, 2020, Sekellick and Sherr, 2024). County estimates of fertilizer and manure applications over 5-year increments (starting in 2002) were allocated equally to the agricultural land use category pixels within the respective counties, and the results were allocated to the catchments.

Contribution of Nitrogen from Groundwater Storage

Groundwater base flow contributions of nitrogen to streams (in the form of nitrate) were estimated and included in the model. A necessary assumption in doing this is that the concentration of the groundwater is relatively constant, and that the load going into the streams is determined by the rate of groundwater discharge to the stream. A second assumption is that the seasonal rate of groundwater discharge to streams from each catchment is approximately equal to the seasonal rate of recharge to each catchment. In this approach, the results of a machine learning model predicting nitrate concentrations in shallow groundwater (Ransom and Kauffman, 2023) were allocated to the Long Island Sound catchments. For each catchment, there is a single concentration representing recent decadal conditions. Time varying recharge rates were available monthly and aggregated to seasonal for years where recharge values were available from 2003 through 2015 (Reitz and Sanford, 2019). The recharge was allocated to the catchments and converted to a total volume of recharge to each catchment by season for those years. Recharge rates for 2000 through 2002 and 2016 through 2020 were set to the average seasonal value by catchment from those years where the recharge was known. Concentrations are multiplied by seasonal volume of groundwater discharge to provide estimates of seasonal nitrate loads being discharged. The units can be converted to kg/season. Seasonal discharge of nitrate from groundwater was thus estimated by this technique of multiplying the estimated long-term concentration of the shallow groundwater by an estimate of groundwater discharge (volume/time) to estimate groundwater load discharged by season.

Land to Water Delivery Variables

Land to water delivery variables are factors that either enhance or retard the transport of nutrients from within the catchments to the stream network. Variables tested and found to be significant land to water delivery predictors in either the nitrogen or phosphorus models include: (1) the seasonal average Enhanced Vegetative Index (EVI) by catchment developed from 8-day composite data NASA's MODIS Enhanced Vegetative Index (EVI), 500-meter resolution (National Aeronautics and Space Administration, 2024); (2) the natural log (ln) of seasonal recharge at a 1-km cell resolution and allocated to the catchments by Reitz and Sanford (2019); (3) the ln of seasonal precipitation compiled from monthly precipitation datasets also at a 1-km cell resolution and allocated by Wieczorek and others (2022b, 2024) to the catchments; (4) the average overland flow distance within the catchment to the stream (Moore and others, 2011); (5) the ln of seasonal recharge (Reitz and Sanford, 2019); and (6) the ln of the soil erodibility factor for uppermost soil horizon (Wolock, 1997).

Aquatic Decay Variables

Aquatic decay (loss) variables were tested in the models to estimate in-stream and reservoir losses. Relating upstream sources to downstream loads requires estimates of loss as nutrient laden water travels through streams and reservoirs. For example, nutrients may be lost through denitrification (nitrogen only), biological uptake, and sedimentation. The SPARROW model includes these as calibration loss coefficients. No tidal monitoring stations were used in the calibration, and as a result, aquatic decay within the tidal reaches was not measured. Predicted loads in tidal reaches must therefore be interpreted as input loads prior to possible aquatic decay within a given tidal reach (and any tidal reaches upstream of it). These estuarine tidal reaches are likely to have different biological communities from the upstream riverine communities and involve mixing of different water salinities and brackish conditions; therefore, the estuarine ecological environment may process nitrogen differently than the upstream riverine environments.

Average seasonal stream flows and associated stream velocities are calculated at each reach (flowline) in the NHD network (McKay and others, 2012) (Schwarz, 2019, Brakebill and others, 2020). Stream flows and stream velocities for each of the 84 seasons came from Schwarz and others (2026). Stream velocity and stream segment length were used to compute the time of travel for the water to pass through each reach. For streams, the decay is directly related to this time of travel and the size of the river. Decay was tested separately for different sized rivers (categorized by temporal ranges in streamflow).

RESULTS

Nitrogen Model Calibration Results

The nitrogen model is calibrated with 3,234 observations of seasonal stream loads representing 21 years of data (2000–2020). The model has a coefficient of determination (R^2) of 0.940, a yield R^2 of 0.777, and the Root Mean Square Error (RMSE) of 0.464. The model fit (natural log of the nitrogen load (in kg/season), predicted versus observed) is shown in figure 6.

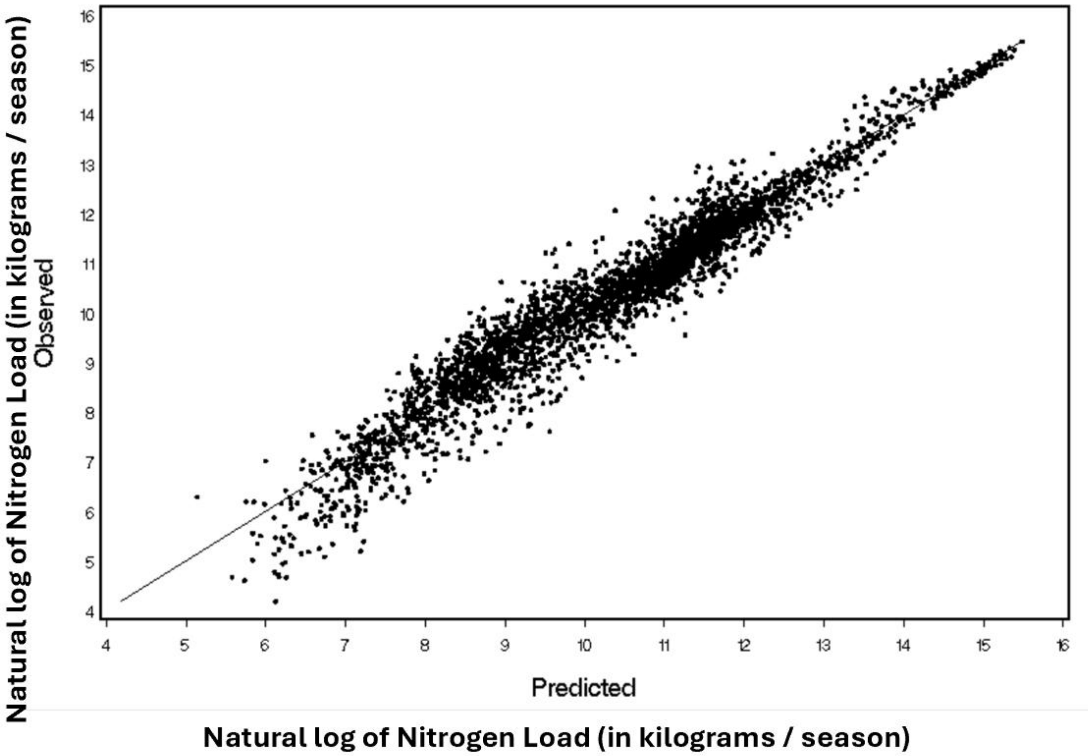

Figure 6. Nitrogen Model – **predicted versus observed**, natural log of the **Nitrogen** load (kg/season) for 3,234 observations.

Of the 13 predictors included in the model, the wastewater point discharge was set to 1 because it is measured and goes directly into the rivers and thus does not need to be estimated through model calibration. Of the remaining 12 predictors, 11 are significant ($p < 0.05$), 10 are highly significant ($p < 0.001$), and 1 nonsignificant predictor (reservoir decay; $p < 0.145$) is included because the reservoir decay was significant at $p < 0.05$ during the early years, when there were more dependent load data in the northern part of the watershed where large reservoirs exist. Calibration coefficient estimates and related coefficient statistics for the nitrogen model are given in table 1.

Table 1. Calibration Coefficient Estimates for the Long Island Sound dynamic seasonal SPARROW Model for Total Nitrogen.

Variable	Model Coefficient	Standard Error of Coefficient	t -value	Probability Level (p-value)	Variance Inflation Factor (VIF)
Municipal Wastewater discharge (kg / season)	1	.	.	.	.
Atmospheric Deposition N (kg / season)	0.106	0.0072	14.7	0	6.74
Snow Cover - Spring (km2)	472	41.7	11.3	0	1.39
Urban Land (km^2)	3.99	0.417	9.59	0	4.60
Baseflow N (kg/season)	0.834	0.0433	19.2	0	3.26
Agricultural manure N (kg / season)	0.0269	0.00196	13.7	0	2.83
Storage (timesteps > 1) (kg / season)	0.324	0.0169	19.2	0	10.4
Storage (first timestep) (kg / season)	1.44	0.307	4.71	0.00000264	1.02
Ln(Precipitation) from the prior season	-0.17	0.0842	-1.99	0.0469	1.41
Ln(Precipitation)	1.14	0.0800	14.2	0	2.94
Enhanced Vegetative Index (EVI)	-0.00064	0.00003	-21.6	0	3.84
Travel Time small streams (less than 70 cubic feet per second) (days)	1.23	0.0590 0.07	20.9	0	3.957
Reservoir Decay (inverse hydrological load - seasonal) (m/year)	1.00	0.6872.62	1.46	0.145	1.23

The coefficient for the seasonal atmospheric deposition of nitrogen (ATN) is 0.106, indicating that on average, about 10.6% of the atmospheric deposition of total nitrogen that falls on the land surface within the Long Island Sound drainage area (above monitoring stations) reaches the stream network. Units on the coefficients are the inverse of the units of the variable. For example, atmospheric deposition has units of kg/season, while the units for its coefficient has units of 1/(kg/season). Like most predictors included in the model, the high "t value," for atmospheric deposition of 14.7, and a Pr > [t] of 0 indicates that the atmospheric deposition 1) plays a major influence on the overall model, and 2) the predictor coefficient is highly significant. The coefficient for the average Snow Cover in Spring (SCS) by catchment, in units of square kilometers (km^2), indicates that, on average, for every 1 km2 of spring snow cover, 472 kilograms (kg) of nitrogen is delivered to the stream network during the spring snowmelt. Similarly, the coefficient for urban land (URB) by catchment of 3.99, in units of square kilometers (km^2), indicates that for every 1 km^2 of urban land, an average of 3.99 kg of nitrogen is delivered to the stream network per season. The coefficient for groundwater baseflow discharge of nitrogen to streams (BFN) of 0.834 indicates that the model response is on average about 17% lower than the estimated groundwater nitrate baseflow input to streams, or that the previous groundwater estimate was high by 17%. This result could indicate nitrogen loss within the stream beds and the near stream (ground water discharge) environment.

For agriculture, seasonal applications of manure (AMN) were significant and could likely be used as a surrogate for general agricultural sources. The low coefficient of 0.027 indicates that on average, only about 2.7% of the N from applied manure reaches the streams each season. The coefficient for storage (ST) of 0.32 indicates that on average, 32% of each season's load gets carried over as storage to the next. For the first seasonal iteration (winter 2000), there were no prior predictions; therefore, initial previous seasonal estimates (ST0) were based on average annual conditions. This was only done to start the models' first iteration, and the coefficient of 1.44 is an artifact of this modeling process.

Three land-to-water delivery model variables, described below, were mean adjusted transformed so that each mean value was zero. This transformation was made so that the source coefficients (described in the previous paragraph) are more interpretable. The first land to water delivery variable, the natural log of the previous season's precipitation has a negative value of -0.17, indicating that the delivery of nitrogen, from the previous season storage, is slowed. This land-to-water delivery variable is applied only to the delivery of nitrogen from the previous season storage. The second land to water delivery variable, the natural log of the precipitation (mm), has a positive coefficient indicating that the natural log of the precipitation (mm) enhances the delivery to the streams of the sources applied to the land surface areas of the catchments (i.e., all sources except for wastewater treatment plant discharges, groundwater discharge, and nitrogen from storage). The third land-to-water delivery variable, the enhanced vegetative index (EVI), has a negative coefficient, indicates that the delivery of nutrients applied to the land is slowed by more vegetative activity within the catchment.

For aquatic decay variables there are two predictors, and both have positive coefficients, which as formulated in the model for the aquatic decay variables, means there is a loss of nutrients during stream and reservoir (or lake or pond) transport. The first predictor (TRAVEL_DAYS_LT70) estimates losses in small streams with flows less than 70 cubic feet per second (ft^3/s). that tend to be wadable. Significant decay was detected within these streams by the model as a function of travel time in days. During seasons of low flow, these conditions of nitrogen loss can extend further downstream (Deacon and others, 2006, Smith and others, 2008). For reservoir decay, a single predictor is used based on the inverse hydrologic load (INVHYDLOADSSN) where the amount of load lost is a function of 1) the load going into the waterbody; 2) the amount of flow going through the waterbody; and 3) the surface area of the waterbody.

Phosphorous Model Calibration Results

Incorporating data from throughout the 21 modeled years (2000–2020), the phosphorus model is calibrated with 2,380 observations of seasonal stream loads. The model R^2 is 0.895; the yield R^2 is 0.882, and the Root Mean Square Error (RMSE) is 0.738. The model fit (natural log of the phosphorus load,in kg/season, predicted versus observed) is shown in figure 7.

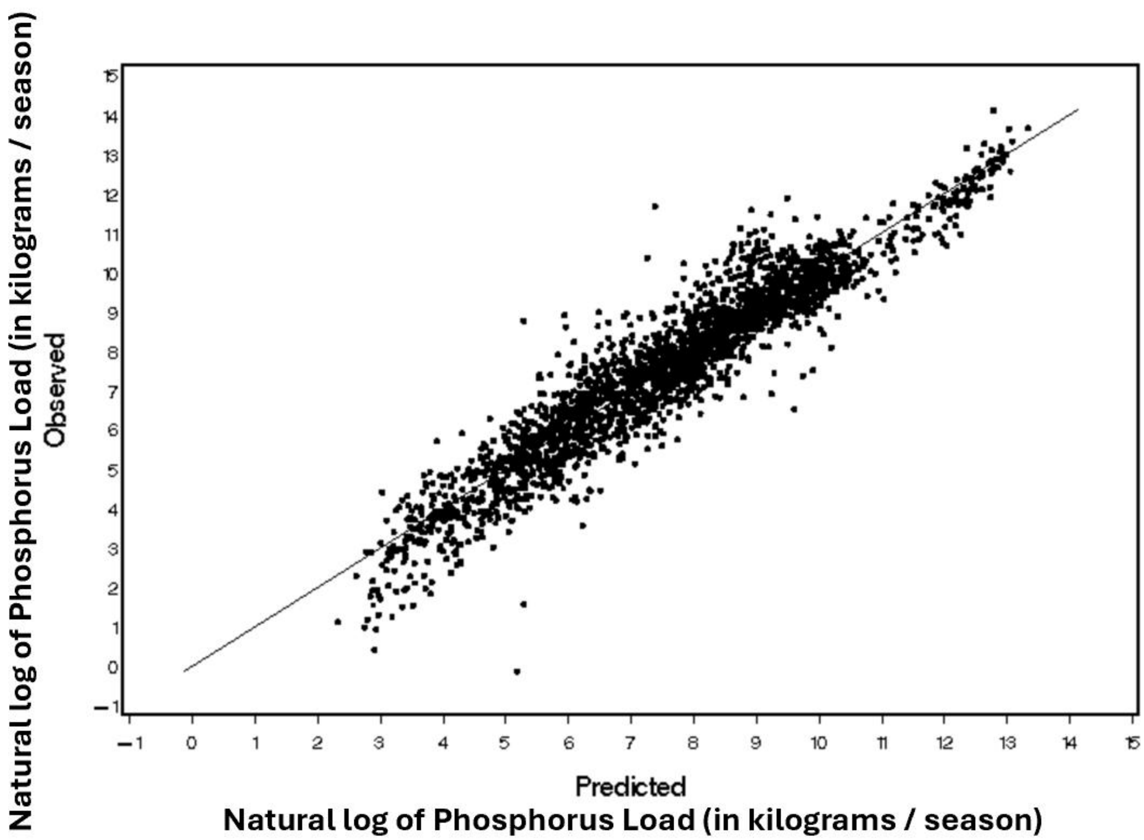

Figure 7. Phosphorus Model – **predicted versus observed**, natural log of the **Phosphorus** load (kg/season) for 2,380 observations.

Eleven predictors are significant, 10 of which are highly significant (p-value < 0.001). The coefficient for points-sources municipal phosphorus (PMP) was set to 1 because it is a measured load going directly into the river. Calibration coefficient estimates and related coefficient statistics for the phosphorus model are given in table 2.

Table 2. Calibration Coefficient Estimates for the Long Island Sound dynamic seasonal SPARROW Model for Total Phosphorous.

Variable	Model Coefficient	Standard Error of Coefficient	t -value	Probability Level (p-value)	Variance Inflation Factor (VIF)
Municipal Wastewater discharge (kg/season)	1	.	.	.	.
Snow Cover - Spring (kg/km^2)	14.7	6.64	2.21	0.0265	1.16
Urban Land (kg/km^2)	1.38	0.0919	15.0	0	2.61
Agricultural Fertilizer P (kg/season)	0.00443	0.000907	4.89	0.00000108	2.94
Agricultural Manure P (kg/season)	0.0226	0.00215	11.0	0	2.46
Atmospheric Deposition N (kg/season)	0.00963	0.000888	10.9	0	3.02
Ln(STATSGO_KUP) Natural log (ln) of the soil erodibility factor for uppermost soil horizon ln(dimensionless) (Wolock, 1997)	3.63	0.141	25.7	0	1.28
Overland-Flow Distance (meters)	-0.348	0.070	-4.97	0.000000722	2.55
Ln(Precipitation in mm)	1.22	0.0592	20.7	0	1.37
Enhanced Vegetative Index (EVI) (unitless)	-0.000175	0.0000164	-10.7	0	1.47
Trave Time small streams (less than 70 cubic feet per second) (in units of days)	1.81	0.0975	18.6	0	2.82
Reservoir Decay (inverse hydrological load - seasonal) (m/year)	99.8	20.0	4.99	0.000000637	1.30

The coefficient for the average Snow Cover in Spring (SCS) by catchment of 14.7 in units of kilograms per square kilometers (kg/km^2) indicates that on average, for every 1 km^2 of spring snow cover, 14.7 kg of phosphorous reaches the stream network during the spring snow melt. The calibration coefficient of 0.00963 for Atmospheric Total Nitrogen (ATN) acts as a surrogate for atmospheric deposition of total phosphorous and indicates that for every 1 kg of atmospheric deposition of total nitrogen, approximately 0.0096 kg of phosphorous reaches the stream network. The coefficient for urban land (URB) by catchment of 1.38, in units of kg/ km^2, implies that on average for every 1 km^2 of urban land, 1.38 kilogram of nitrogen reaches the stream network per season. For agriculture, the coefficient for seasonal applications of manure (AMP) in kg was significant. The low coefficient of 0.0226 indicates that an average of 2.66% of the phosphorous from applied manure reaches the streams. Similarly, the coefficient for seasonal applications of fertilizer to agricultural lands (AFP) was significant. The low coefficient of 0.00443 implies that an average only about 0.44% of the applied phosphorous in fertilizer reaches the streams.

In the phosphorus model, the four land-to-water delivery variables were mean adjusted. Within the model, each land-to-water delivery variable was transformed so that its mean value was zero. This transformation makes the source coefficients more interpretable, as discussed in the previous paragraph. Two land-to-water delivery variables, the natural log of the soil permeability from the STATSCO database and the natural log of precipitation, both have positive coefficients, indicating that they enhance the delivery to the streams of the sources applied to the land area of the catchment (i.e., all sources except for wastewater treatment plant discharges going directly into the streams and storage). The two-remaining land-to-water delivery variables, the enhanced vegetative index (EVI) and the natural log of the average overland distance within the catchment to the streams, have negative coefficients, indicating that the delivery of nutrients applied to the land is slowed by more vegetative activity within the catchment and greater distance to the streams.

For aquatic decay variables, the two predictors both have positive coefficients; as formulated in the model for the aquatic decay variables, this means there is a loss of nutrients during stream and reservoir transport (or through other water bodies). As in the nitrogen model, the first predictor (TRAVEL_DAYS_LT70) estimates losses in small streams with flows less than 70 cubic feet per second (ft^3/s) that tend to be wadable. Significant decay was detected in these streams by the model as a function of travel time in days. For reservoir decay, a single predictor is used based on the inverse hydrologic load (INVHYDLOADSSN) where the load lost is a function of 1) the load going into the waterbody; 2) the amount of flow going through the waterbody; and 3) the surface area of the waterbody.

Nutrient Estimates

Model results include estimates of total nitrogen loads, phosphorus loads, and source contributions and their confidence intervals for all 20,977 network flowlines within the stream network (Moore and others, 2026). Of the 20,977 flowlines, four are selected here for discussion to summarize model estimates. The four flowlines are at the mouths of the four largest rivers: the Connecticut, Housatonic, Thames, and Pawcatuck Rivers.

Connecticut River – Nutrient Loads

The Connecticut River is the largest watershed tributary to Long Island Sound (figure 1), and the estimated seasonal loads at the mouth of the Connecticut River for 2000–2020 are presented in figure 8. The highest peaks of nitrogen loads coincide with tropical storms during the fall of 2005. The second highest peak of nitrogen loads coincide with the spring snowmelt of 2011. The third largest peak is associated with atmospheric deposition and snowmelt during the winter and spring of 2008. The years of greatest spring snowmelt are dispersed throughout the record but have decreased in recent years.

The total atmospheric deposition of nitrogen is a dominant predictor throughout all four seasons, with the fall and winter seasons typically at high levels, with associated spring nitrogen loads comparable to, or second only to, spring snowmelt loads. Storage from the previous season is often the third-largest load source and is often high in the winter or spring following the previous fall or winter load.

Point sources from municipal treatment plants were often the sources with the highest loads prior to 2015, but have not been the sources with the highest loads after 2015. Point sources have a seasonal component with higher estimated loads associated with the winters and springs, with high atmospheric deposition and snowmelt, perhaps representing the atmospheric deposition or snowmelt captured by combined sewer overflows (CSOs) that exist within the watershed. The lowest loads are associated with summer. There also is an overall rise in point source nitrogen loads from 2001 to 2005, undulating point source loads from 2006 to 2010, then decreasing loads from 2011 to 2017 and then a rise to 2019. This pattern may be the result of competing factors that include improved water treatment technology being used at treatment plants; decreasing point source loads of nitrogen; and increasing populations and areas being serviced by wastewater treatment facilities. The fifth-most prominent source seems to be groundwater baseflow contributions of nitrogen. Peak loads for nitrogen from groundwater discharge to streams tend to be in the fall or winter, and lowest in the summer. The regular pattern during 2000–2003 and again during 2016–2020 demonstrates a limitation in the available data where mean seasonal recharge conditions had to be used instead of year-season specific recharge, which conceptually pushes the groundwater through the aquifer system into the stream. The sixth-most prominent source is the agricultural source of manure application, which is used as a surrogate for other agricultural sources. This source has a seasonal component that is likely associated with seasonality of the three land to water delivery factors. Urban land use is last in the list of source contributors and has the same seasonality pattern as the agricultural source that also appears associated with the land-to-water delivery factors in the model.

The previous steady state SPARROW model (Moore and others, 2011) representing mean annual source conditions detrended to 2002 produced an estimate of 15,641 metric tons of N per year. For comparison with the seasonally varying estimates of total N (shown in figure 8), the average seasonal estimate from the earlier model for 2002 is **3,910** metric tons of nitrogen/season (i.e., 15,641 metric tons/year).

Estimated Seasonal Nitrogen Loads at Mouth of Connecticut River

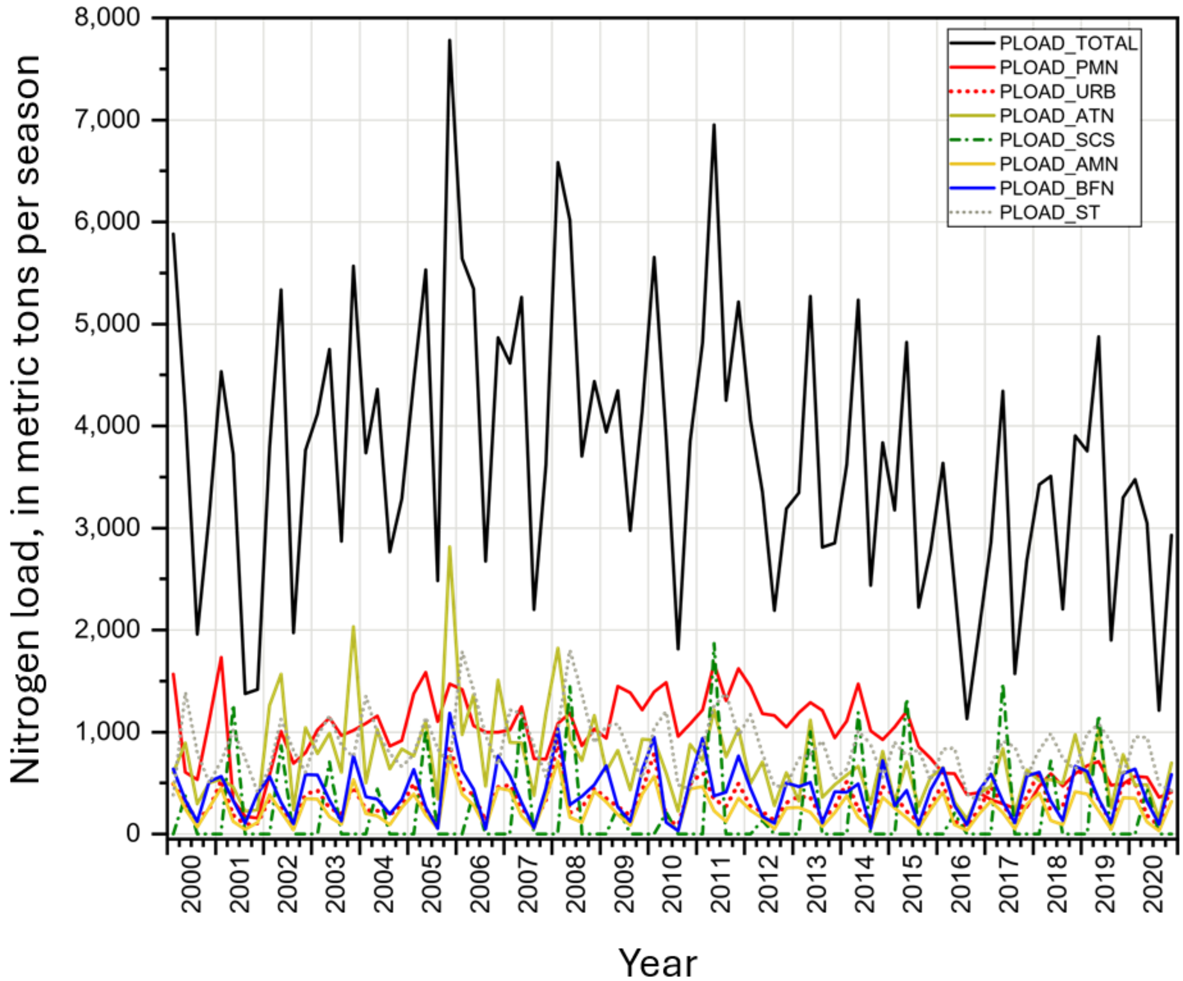

Figure 8. Estimated Seasonal Nitrogen Loads at the mouth of the Connecticut River with estimated seasonal source contributions for years 2000 through 2020. Predicted Nitrogen Load Total (PLOAD_TOTAL); Point Source Municipal Nitrogen (PMN); Urban Land (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Manure Nitrogen (AMN); BaseFlow Nitrogen (BFN); and Storage (ST).

Connecticut River – Phosphorus Load Estimates

The estimated seasonal phosphorous loads at the mouth of the Connecticut River are presented for years 2000 through 2020 in figure 9. The average total seasonal loads vary widely throughout the four seasons, with the highest peaks being associated with several sources affected by precipitation which contain or help deliver phosphorus to the streams. There is manure and to a lesser extent fertilizer spread on agricultural fields (containing phosphorus which is delivered to the streams by water from precipitation); atmospheric deposition of phosphorus (using nitrogen as a surrogate); and point source discharge from wastewater treatment plants. The clear response of point source discharge to heavy precipitation presumably represents storm water captured by combined sewer overflows (CSOs) that exist within the watershed. Spring meltwater plays a smaller role in the phosphorus model than in the nitrogen model. Although point source phosphorus loads vary annually and seasonally, there is an overall increase from 2001 to 2005 and a gradual decrease from 2005 to 2017. This general decrease in point source phosphorous loads may be the result of improved water treatment technology being used at treatment plants, and the separation of more stormwater away from municipal wastewater.

Point sources from municipal treatment plants are the largest source contributor through this 21-year modeled period. Point sources have a seasonal component with the higher estimated loads associated with periods of high precipitation or snowmelt, and lower loads associated with summer or low precipitation. Third in overall importance (behind point sources and atmospheric deposition) is urban lands, which indicates a seasonal undulation and seems to have been associated with gradually increasing phosphorous loads, on average, from just below 100 to just above 100 metric tons per season. The two agricultural sources of manure and fertilizer application have the next highest phosphorus loads and together make up a sizable contribution. Both have a seasonal undulation similar to the phosphorous loads from urban lands that seem related to the land-to-water delivery variables. Lastly, snow cover represents the spring snowmelt and has peak phosphorus loads that in more recent years frequently exceeded the two agricultural sources (figure 9).

Estimated Seasonal Phosphorus Loads at Mouth of Connecticut River

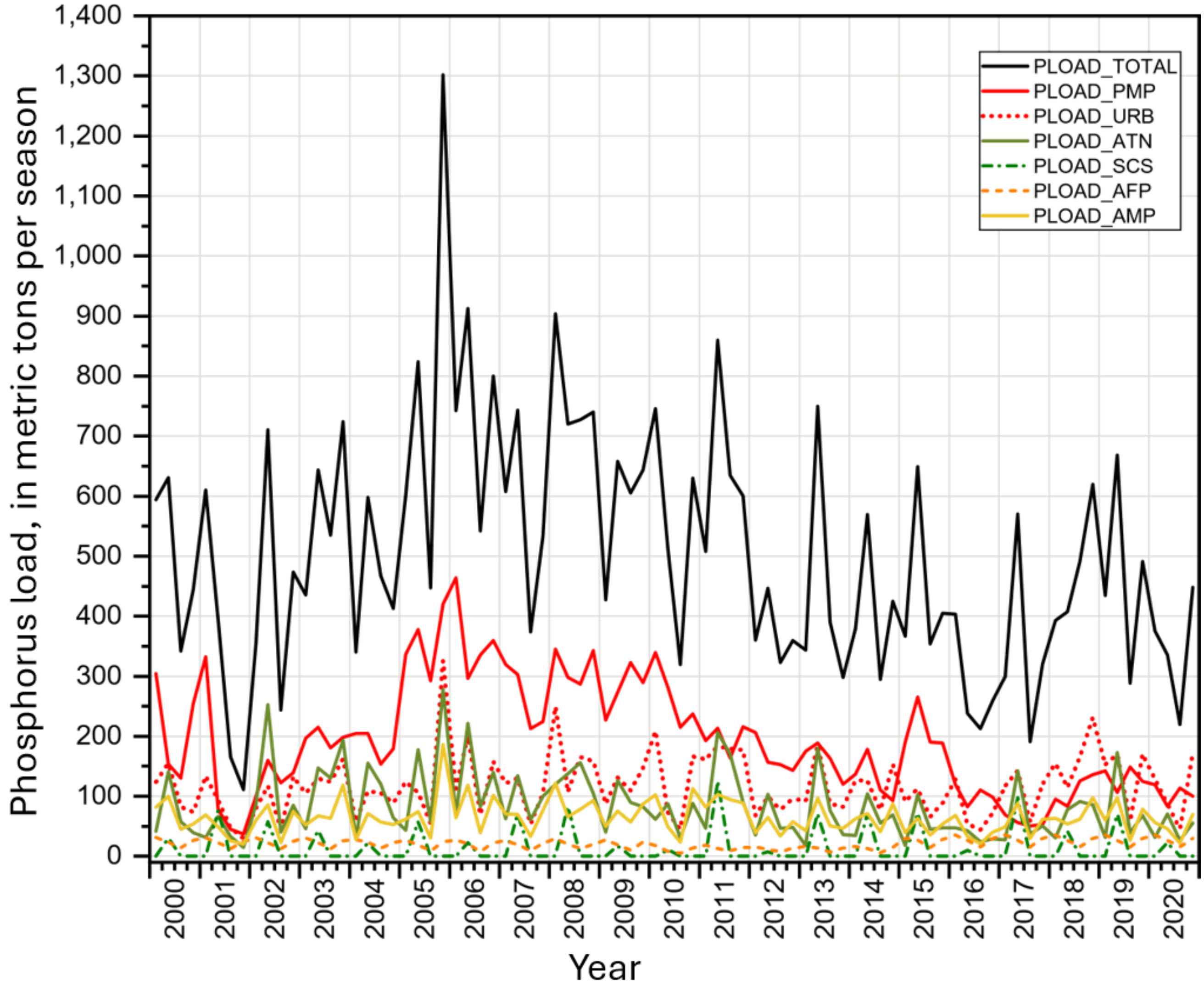

Figure 9. Estimated Seasonal Phosphorous Loads at the mouth of the Connecticut River for years 2000 through 2020. Predicted Phosphorus Load Total (PLOAD_TOTAL); Point Source Municipal Phosphorus (PMP); Urban Land (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Fertilizer Phosphorus (AFP); and Agriculture Manure Phosphorus (AMP).

Housatonic River – Nutrient Loads

The second largest watershed tributary to Long Island Sound is the Housatonic River (figure 1). The estimated seasonal loads at the mouth of the Housatonic River, with estimated seasonal contributions for years 2000 through 2020, are presented in figure 10. Most of the seasonal load contributions to the Housatonic River are like those of the Connecticut River, with a few notable exceptions. First, the snowmelt contribution is almost nonexistent, occurring in only a few years and at very low levels. This is likely due to the fact that the Housatonic River watershed is farther south and less mountainous than the Connecticut River watershed. Secondly, point sources more prominently influence total nitrogen loads in the Housatonic River. There was a general increase in point sources contributions from 2001 up to 2006, plateaued during 2006-2011, and then declined from 2012-2017. Wastewater treatment point source loads were very small (less than 50 metric tons per season) by 2017.

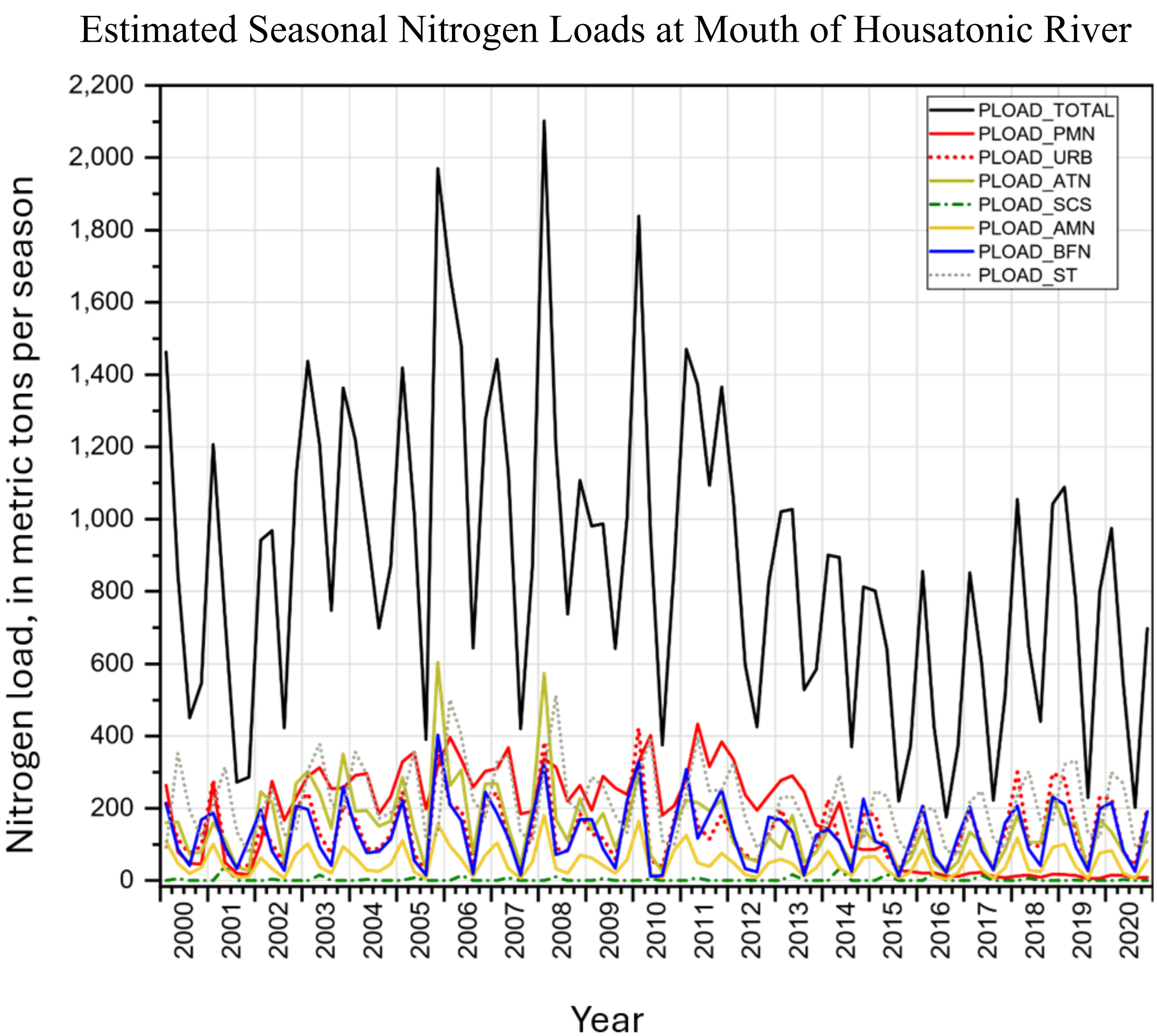

Figure 10. Estimated Seasonal Nitrogen Loads at the mouth of the Housatonic River with estimated seasonal source contributions for years 2000 through 2020. Predicted Nitrogen Load Total (PLOAD_TOTAL); Point Source Municipal Nitrogen (PMN); Urban Land (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Manure Nitrogen (AMN); BaseFlow Nitrogen (BFN); and Storage (ST).

Estimated seasonal phosphorous loads in the Housatonic River for years 2000 through 2020 are shown in figure 11. Most of the seasonal load contributions to the Housatonic River are similar to those of the Connecticut River, with a few exceptions. Similar to nitrogen loads, spring snowmelt phosphorus contributions are almost nonexistent, occurring only during a couple springs at very low levels. Another notable factor is the way point sources have prominently affected phosphorus loads. Changes in point sources have resulted in prominent changes in the overall total loads (figure 11). Point source loads decreased from 2000 to 2001 and abruptly increased in 2002.Loads were highly variable until 2012, then decreased until 2015 and were almost negligible until 2017, when loads began to increase. This increase in loads may be an indication that more of the population was being served by municipal wastewater treatment facilities delivering phosphorous loads to the rivers than in earlier years. Phosphorus point source loads, however, began decreasing from 2011 to 2016, perhaps because of improvements in the removal of phosphorous from the wastewater from the treatment plants and separation and removal of storm water.

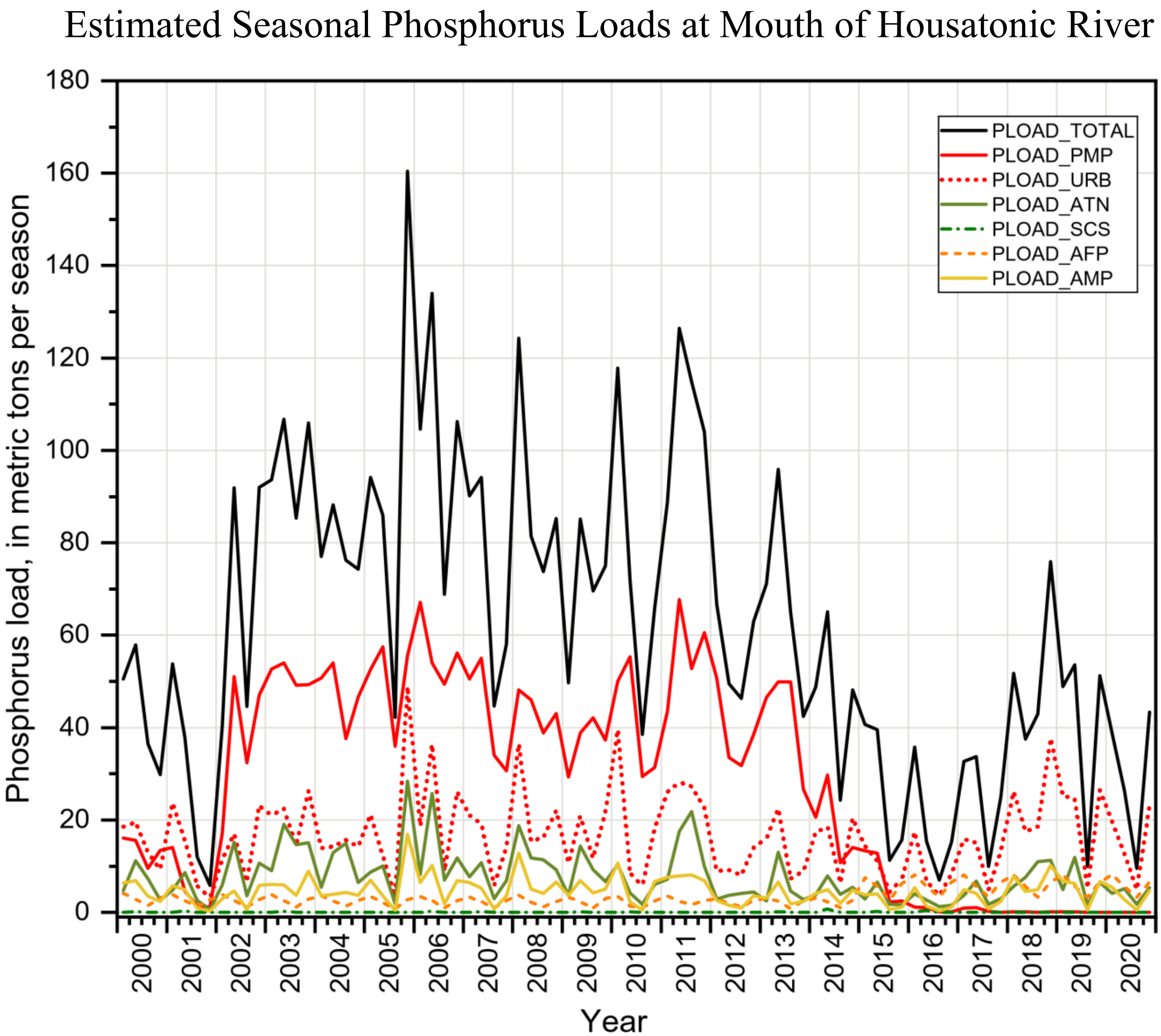

Figure 11. Estimated Seasonal Phosphorous Loads at the mouth of the Housatonic River for years 2000 through 2020. Predicted Phosphorus Load Total (PLOAD_TOTAL); Point Source Municipal Phosphorus (PMP); Urban Land (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Fertilizer Phosphorus (AFP); and Agriculture Manure Phosphorus (AMP).

Thames River – Nutrient Loads

The third-largest watershed tributary to Long Island Sound is the Thames River (figure 1). The estimated seasonal nitrogen and phosphorus loads at the mouth of the Thames River for years 2000 through 2020 are presented in figures 12 and 13. Most of the seasonal load contributions to the Thames River are similar to the Housatonic River with the notable exception of the wastewater treatment plant discharge. In the Thames River watershed, there was a sudden rise in wastewater discharge of nitrogen between 2001 and 2002. From about 2004 to the end of the modeled record in 2020, there was a steady decrease in point source loads, with just a few deviations. Agricultural sources of nitrogen (manure as a surrogate) and phosphorous (fertilizer and especially manure) seem to be relatively more important in the Thames River watershed than in the other major watersheds for tributary rivers to Long Island Sound.

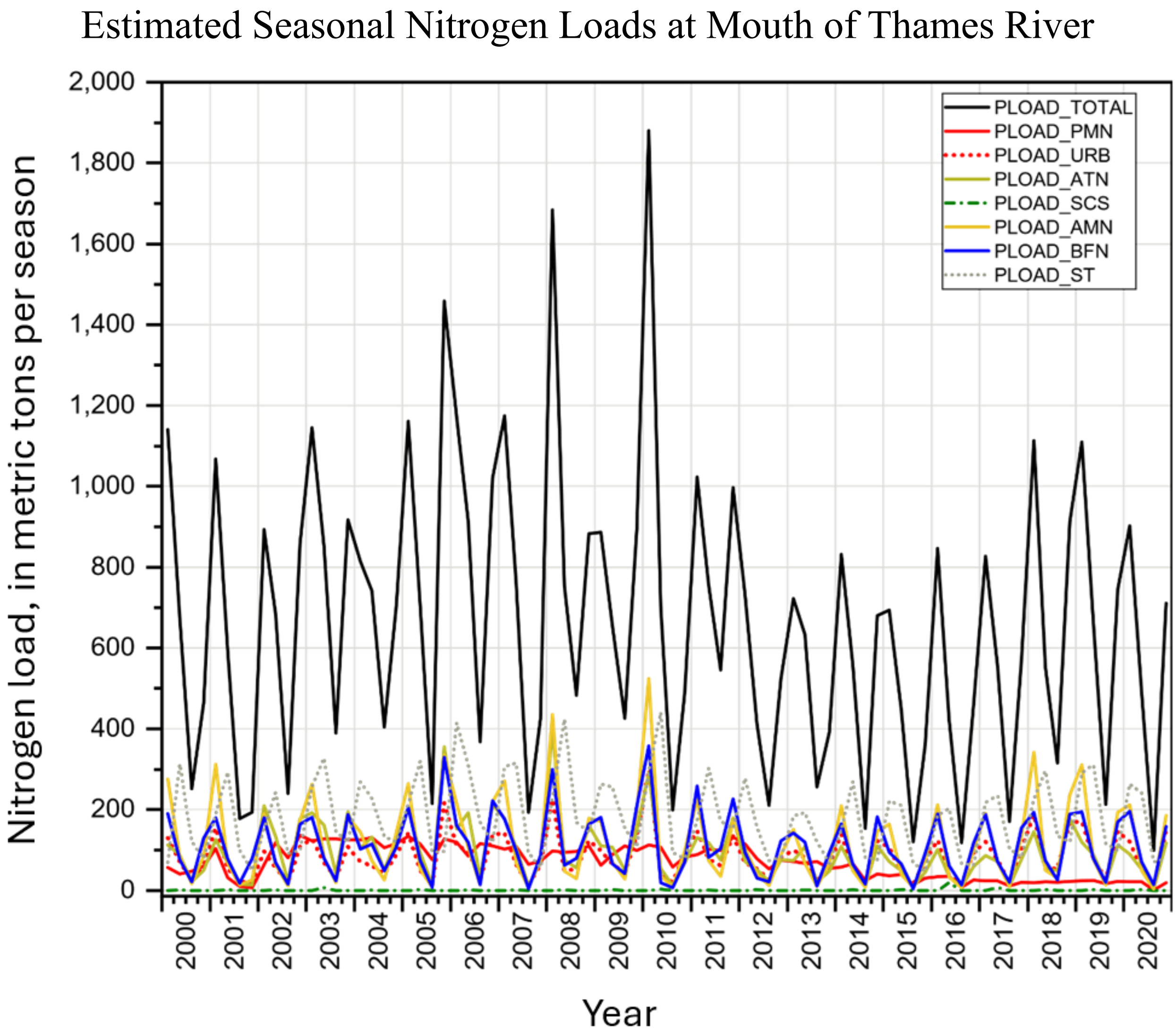

Figure 12. Estimated Seasonal Nitrogen Loads at the mouth of the Thames River with estimated seasonal source contributions for years 2000 through 2020. Predicted Nitrogen Load Total (PLOAD_TOTAL); Point Municipal Nitrogen (PMN); Urban and Developed (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Manure Nitrogen (AMN); BaseFlow Nitrogen (BFN); and Storage (ST).

Estimated Seasonal Phosphorus Loads at Mouth of Thames River

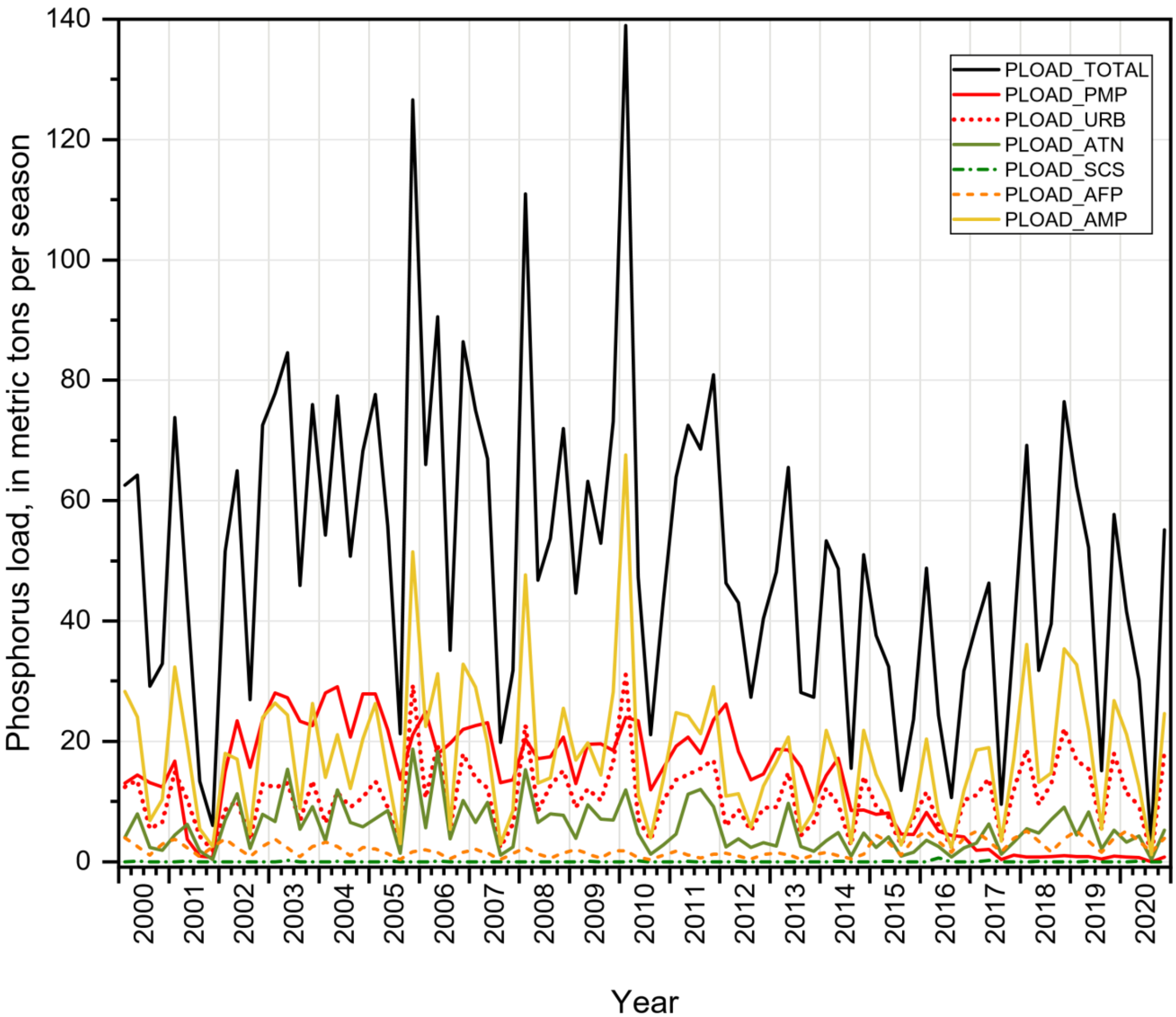

Figure 13. Estimated Seasonal Phosphorous Loads at the mouth of the Thames River for years 2000 through 2020. Legend abbreviations Predicted Phosphorus Load Total (PLOAD_TOTAL); Point Municipal Phosphorus (PMP); Urban Land Developed (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Fertilizer Phosphorus (AFP); and Agriculture Manure Phosphorus (AMP).

Pawcatuck River – Nutrient Loads

The fourth-largest watershed tributary to Long Island Sound is the Pawcatuck River (figure 1). The estimated nitrogen and phosphorus seasonal loads at the mouth of the Pawcatuck River for years 2000 through 2020 are presented in figures 14 and 15, respectively. Aside from being almost an order of magnitude smaller in area and in total nitrogen loads than the Housatonic and Thames watersheds, the Pawcatuck River watershed has a similar pattern for total load (for N loads compare figure 14 below with figures 10 and 12; and for P loads compare figure 15 with figures 11 and 13). However, the water treatment point source distribution remains more steady compared to the other watersheds, with a few exceptions.

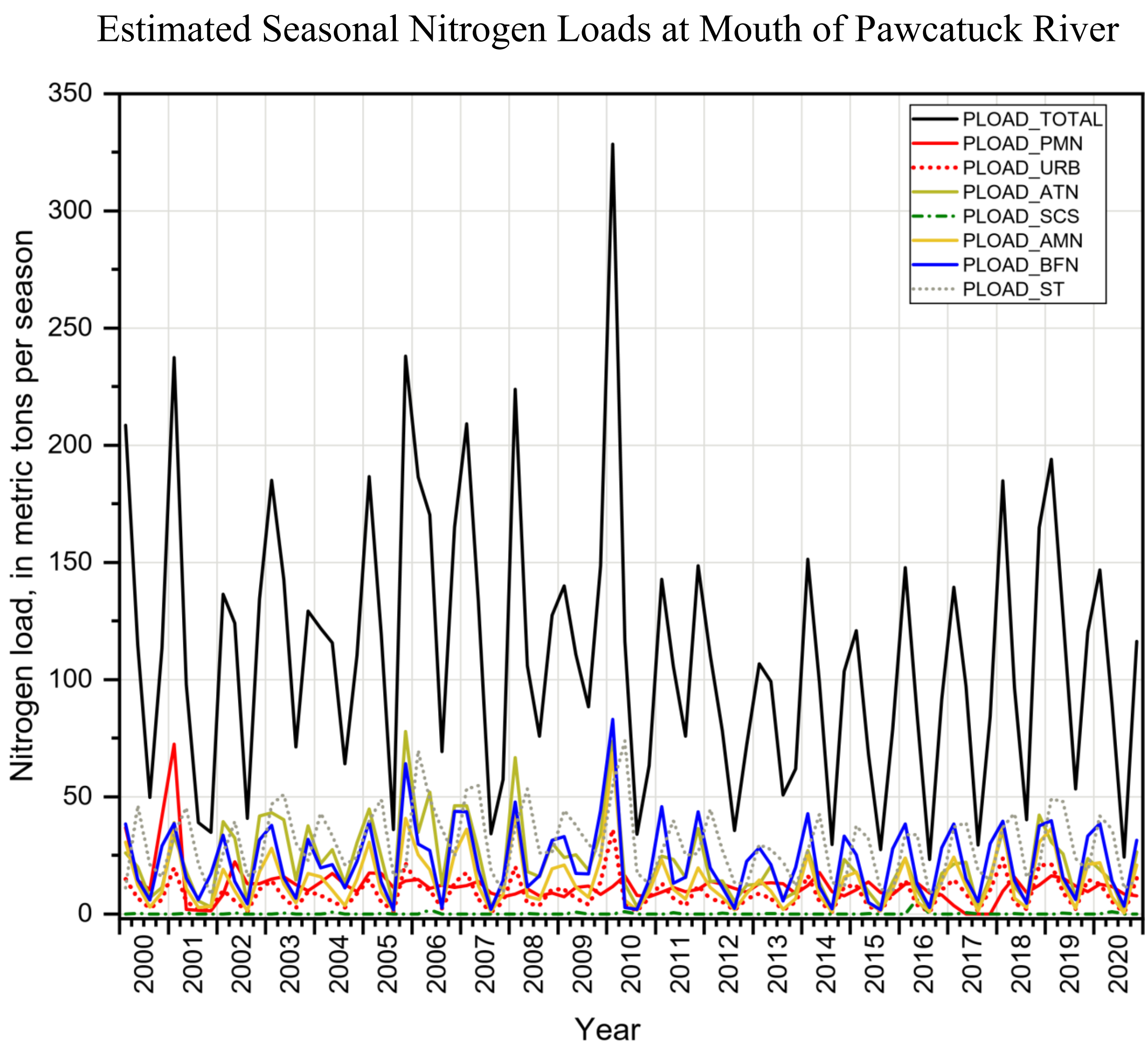

Figure 14. Estimated Seasonal Nitrogen Loads at the mouth of the Pawcatuck River with estimated seasonal source contributions for years 2000 through 2020. Predicted Nitrogen Load Total (PLOAD_TOTAL); Point Source Municipal Nitrogen (PMN); Urban Land Developed (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Manure Nitrogen (AMN); BaseFlow Nitrogen (BFN); and Storage (ST).

Estimated Seasonal Phosphorus Loads at Mouth of Pawcatuck River

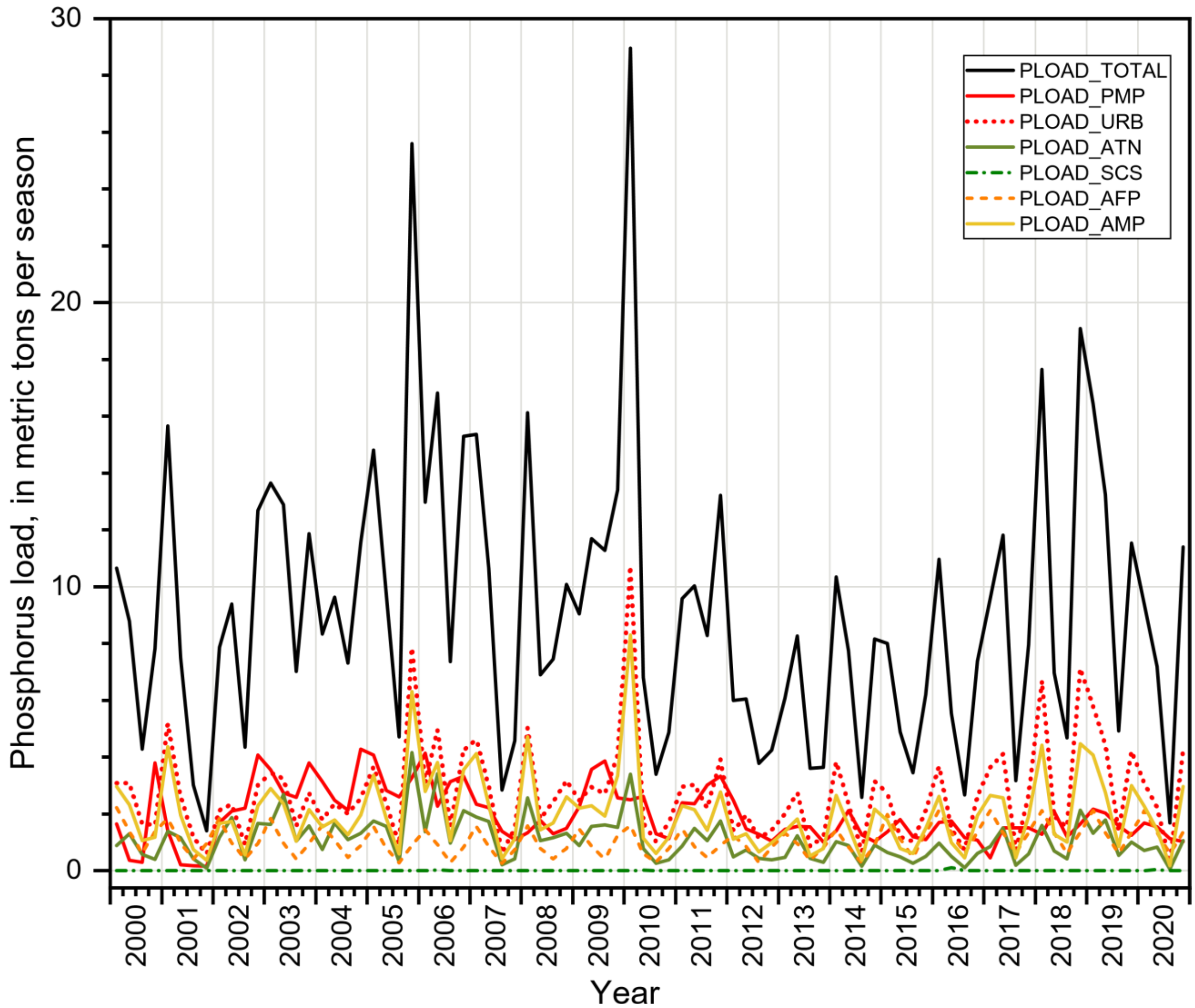

Figure 15. Estimated Seasonal Phosphorus Loads at the mouth of the Pawcatuck River with estimated seasonal source contributions for years 2000 through 2020. Predicted Phosphorus Load Total (PLOAD_TOTAL); Point Source Municipal Phosphorus (PMP); Urban Land Developed (URB); Atmospheric Deposition Nitrogen (ATN); Snow Cover Spring (SCS); Agriculture Fertilizer Phosphorus (AFP); and Agriculture Manure Phosphorus (AMP).

DISCUSSION

Nitrogen and phosphorus exhibit characteristics and load distributions that vary dynamically with time, and the study of these nutrients benefits from use of seasonally dynamic SPARROW modeling. Both N and P SPARROW models show wide ranges in load distribution with time. Both nutrients respond similarly to changes in source contributions. There are, however, differences between the two nutrient models. This may be in part due to different characteristics of the nutrients. Nitrogen is a gas that makes up most of the earth's atmosphere. In water, nitrogen can be in an ionic state, such as $NO3^-$, which is highly soluble. Phosphorous, however, is found in minerals, and most of its inorganic compounds have low solubility. Phosphorus tends to attach itself to sediment particles and be transported with suspended sediment (Hem, 1985). Both elements are used by biota as nutrients and are thus found in municipal wastewater and in manure used to fertilize crops.

The similarities and differences between how nitrogen and phosphorus behave in the models are presented in figures 8 through 15. The high solubility of $NO3^-$ resulted in our ability to represent nitrogen in groundwater baseflow discharging into streams in the nitrogen model. The atmospheric deposition of nitrogen plays a dominant role in the nitrogen model due to both wet and dry deposition. The data indicate that phosphorus also has an atmospheric mode of transport and deposition. However, that may be primarily as dry atmospheric deposition (Hem, 1985). Sewage discharge from municipal wastewater treatment plants also plays a dominant role for both nutrients in the models, especially phosphorous. Both models have shown major reductions from municipal wastewater in recent years. Manure used in agriculture plays a significant role in both models. Storage is significant in the nitrogen model. Nitrogen dissolved in water and stored within the network from one season to the next contributes to the total nitrogen load. Phosphorous, however, is prone to attach to particles and thus is more likely to settle out and not contribute to the total load in subsequent seasons.

CONCLUSIONS

This paper demonstrates the capability and utility of a modeling technique where seasonal timesteps are used to model nutrients within streams and rivers. SPARROW is a modeling technique that incorporates statistically significant predictors. Results from seasonal time steps, for reaches (flowlines) of interest, can be examined to better understand different parts of the Long Island Sound watershed. Individual catchments, and smaller watersheds can be examined, as well as entire watersheds of major rivers.

Variables that are examined include nutrient sources, land-to-water delivery factors, and aquatic decay. A nitrogen source variable representing the storage of nitrogen, from one season into the next, represented a significant source of nitrogen in the model; however, seasonal storage was not a significant source of phosphorus in the phosphorus model. Phosphorus is well known for a tendency to attach itself to sediment particles, which may end up stored in the sediment (or in the case of groundwater, attached to the aquifer matrix), with much less stored and readily transported from within the water column.

Population on septic also was also not a significant source of nitrogen or phosphorus. Phosphorus has the tendency to attach itself to sediment particles such as the groundwater matrix material or even the sludge within septic tanks that presumably gets treated elsewhere for this study. Nitrogen is more soluble, may move through the system more readily, and is represented in the model as a groundwater baseload source.

Several additional newly available nutrient source attributes were included: a term representing the spring snowmelt contribution; a term representing groundwater contributions; and a third term representing surface water storage from the previous season. Groundwater baseflow and seasonal surface water storage were found to be significant sources of nitrogen. Spring snowmelt was found to be a significant source of both nitrogen and phosphorus. Spring snowmelt especially affects the northern mountainous parts of the Long Island Sound model area, where the snow cover is the greatest and extends further into the spring.

Atmospheric deposition of nitrogen within the Long Island Sound watershed was found to be an important and significant predictor in both the nitrogen and the phosphorous models. In the phosphorous model, this is likely because the atmospheric deposition functioned as a surrogate for phosphorous. The SPARROW model likely recognized a spatial pattern of the unmonitored phosphorus deposition that was similar to the monitored atmospheric deposition of nitrogen. Atmospheric deposition of phosphorous should receive more attention in future nutrient research and be measured directly. Nutrient loads from atmospheric deposition vary widely seasonally and annually.

ACKNOWLEDGMENTS

This project was funded by the Long Island Sound Study (LISS) a coordinated effort by the U.S. Environmental Protection Agency (EPA), and the States of New York, Connecticut, and other New England States, and communities within the region which share the common goal of protecting and restoring the health of the aquatic environment of Long Island Sound. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

The authors thank Naomi Detenbeck of the EPA for her coordinated LISS efforts to adapt a tool, the River Basin Export Reduction Optimization Support Tool (RBEROST), and to apply the results from this study, to identify potential ways to reduce nitrogen and phosphorus loads to Long Island Sound. We thank Noah Schmadel and Catherine Chamberlin for their constructive reviews of the manuscript. And we thank Gregory Schwarz, who wrote the code which makes SPARROW modeling possible, including these Long Island Sound seasonally dynamic nitrogen and phosphorus SPARROW models. Thank you all!

DATA AVAILABILITY

All dependent data (seasonal Nitrogen and Phosphorous loads); all predictor data; all model results; and the model source code are presented in Moore and others (2026). Additional model results and source code presented there are for bootstrap analyses of the Nitrogen and Phosphorus SPARROW models. Both bootstrap analyses are based on the computation of 200 sets of model coefficients, producing predictions that reflect a full range of uncertainty included in the model (Schwarz et al., 2006).

REFERENCES CITED

Ator, S.W., 201., Spatially referenced models of streamflow and nitrogen, phosphorus, and suspended-sediment loads in streams of the Northeastern United States, U.S. Geological Survey Scientific Investigations Report 2019–5118, 57 p.

Brakebill, J.W., Schwarz, G.E., and Wieczorek, M.E., 2020. An enhanced hydrologic stream network based on the NHDPlus medium resolution dataset, U.S. Geological Survey Scientific Investigations Report 2019–5127, 49 p.

Chamberlin, C., N.A. Detenbeck, M. Ten Brink, A. Le, K. Munson, I. Morin, M. Marks, AND Y. Li., 2022, RBEROST Code and User Guide. U.S. Environmental Protection Agency, Washington, DC

Deacon, J.R., Smith, T.E., C.M. Johnston, R.B. Moore, R.M Weidman, R.M., and L.J. Blake, 2006. Assessment of total nitrogen in the Upper Connecticut River Basin in New Hampshire, Vermont, and Massachusetts, December 2002– September 2005. U.S. Geological Survey Scientific Investigations Report 2006–5144, 89 p.

Detenbeck, N., A. Piscopo, M. Tenbrink, C. Weaver, A. Morrison, T. Stagnitta et al., 2018. Watershed Management Optimization Support Tool v3. U.S. Environmental Protection Agency, Washington, DC, EPA/600/C-18/001. https://www.epa.gov/hydrowq/wmost. Accessed 2025.

Dewitz, J., 2023. National Land Cover Database (NLCD) 2021 Products: U.S. Geological Survey data release, https://doi.org/10.5066/P9JZ7AO3. Accessed 2025.

Falcone, J. 2020. Estimates of County-Level Nitrogen and Phosphorus from Fertilizer and Manure from 1950 through 2017 in the Conterminous United States: U.S. Geological Survey Open-File Report 2020–1153, 20 p.

Hall, D. K., G.A. Riggs, and V.V. Salomonson, 2006. MODIS/Terra Snow Cover 5-Min L2 Swath 500m. Version 5. Boulder, Colorado USA: NASA National Snow and Ice Data Center Distributed Active Archive Center. https://nsidc.org/data/mod10_l2/versions/61. Accessed 2025.

Hem, J.D., 1985. Study and interpretation of the chemical characteristics of natural water (3rd ed.): U.S. Geological Survey Water Supply Paper 2254, Document: xii, 263 p., 4 pl.

Hirsch, R.M., D.L. Moyer, and S.A. Archfield, 2010. Weighted Regressions on Time, Discharge, and Season (WRTDS), With an Application to Chesapeake Bay River Inputs. Journal of the American Water Resources Association 46(5):857-880.

Lee, C.J., R.M. Hirsch, G.E. Schwarz, D.J. Holtschlag, S.D. Preston, C.J. Crawford, and A.V. Vecchia, 2016. An evaluation of methods for estimating decadal stream loads, Journal of Hydrology, Volume 542, 2016, p. 185-203

Long Island Sound Partnership, 2026, Nitrogen Loading - Long Island Sound Partnership. Accessed 15 August 2026.

McKay, L.D., T.R. Bondelid, T.G. Dewald, C.M. Johnston, R.B. Moore, and A.H. Rea, 2012. NHDPlus Version 2 User Guide NHDPlusV2 User Guide, https://www.epa.gov/system/files/documents/2023-04/NHDPlusV2_User_Guide.pdf. Accessed 2025.

Moore, R.B., C.M. Johnston, K.W. Robinson, and J.R. Deacon, 2004, Estimation of total nitrogen and phosphorus in New England streams using spatially referenced regression models. U.S. Geological Survey Scientific Investigations Report 2004-5012, 42 p

Moore, R. B., C.M. Johnston, R.A. Smith, and Bryan Milstead, 2011. Source and Delivery of Nutrients to Receiving Waters in the Northeastern and Mid-Atlantic Regions of the United States. Journal of the American Water Resources Association 47(5):965-990.

Moore, R.B., S.J. Stanton, and Laura Hayes, 2026, Long Island Sound nitrogen and phosphorus SPARROW models, including model inputs and outputs, 2000-2020: U.S. Geological Survey data release, https://doi.org/10.5066/P13MNQCH. Accessed 24 July 2026.

Multi-Resolution Land Characteristics Consortium, 2021. National land cover database for 2001, 2004, 2006, 2011, 2013, 2016, 2019. https://www.usgs.gov/centers/eros/science/national-land-cover-database. Accessed 2025.

National Aeronautics and Space Administration's MODIS Enhanced Vegetative Index (EVI), MOD09A1G_EVI - MODIS/Terra Gap-Filled, Smoothed EVI 8-Day L4 500m SIN Grid. 2024. https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD09A1G_EVI. Accessed January 2024.

National Atmospheric Deposition Program, 2023. National Atmospheric Deposition Program's (NADP) Long-Term Monitoring Networks. Accessed January 2024.

New England Interstate Water Pollution Control Commission, 2026. Long Island Sound Partnership https://neiwpcc.org/program-partners/long-island-sound-partnership/. Accessed May 2026.

New York State Department of Environmental Conservation and Connecticut Department of Environmental Protection, 2000. A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound. 73 pp.

Ransom, K.M., and L.J. Kauffman, 2023. Data for Machine Learning Predictions of Nitrate in Shallow Groundwater in the Conterminous United States. U.S. Geological Survey data release. https://doi.org/10.5066/P9RT579Z. Accessed 9 December 2025.

Reitz, M., and W.E. Sanford, 2019. Modern monthly effective recharge maps for the conterminous U.S., 2003-2015. U.S. Geological Survey data release, https://doi.org/10.5066/P9NRVAQ5. Accessed 20 November 2025.

Schmadel, N., Harvey, J., Schwarz, G.E., 2021. Seasonally dynamic nutrient modeling quantifies storage lags and time-varying reactivity across large river basins. Environmental Research Letters, v. 16, no. 9, 095004, 11 p.

Schmadel, N.M., O.L. Miller, S.W. Ator, M.P. Miller, G.E. Schwarz, D.M. Robertson, A.J. Sekellick, K.D. Skinner, K.D., and D.A. Saad, 2024. Seasonally varying contributions of contemporaneous and lagged sources of instream total nitrogen and phosphorus load across the Illinois River basin. Science of the Total Environment, v. 955, 176816, 13 p.

Schwarz, G.E., A.B. Hoos, R.B., Alexander, R.A, Smith., 2006. The SPARROW Surface Water-Quality Model—Theory, Applications and User Documentation. U.S. Geological Survey Techniques and Methods, Book 6, Chapter B3, The SPARROW Surface Water-Quality Model—Theory, application and user documentation. Online only.

Schwarz, G.E., 2019. E2NHDPlusV2_us: Database of Ancillary Hydrologic Attributes and Modified Routing for NHDPlus Version 2.1 Flowlines. U.S. Geological Survey data release. https://doi.org/10.5066/P986KZEM. Accessed 17 December 2025.

Schwarz, G.E., N.M. Schmadel, A.J. Sekellick, 2026. Seasonal streamflow enhanced unit runoff method estimates across the conterminous U.S., 2000 through 2020. U.S. Geological Survey data release. https://doi.org/10.5066/P1HK8PE7. Accessed 1 June 2026.

Sekellick, A.J. and C.E. Sherr, 2024. Nitrogen and phosphorus inputs from fertilizer and manure in the Continental United States, 2002-2017. U.S. Geological Survey data release, https://doi.org/10.5066/P9WDBIXC. Accessed 17 December 2025.

Skinner, K.D., Murray, E.M., and Murray, D.L., 2024. Point-Source Nutrient Loads to Streams of the Conterminous United States, 1999-2020. U.S. Geological Survey data release. https://doi.org/10.5066/P13DL6P9. Accessed 17 December 2025.

Smith, R.A., G.E. Schwarz, and R.B. Alexander, 1997. Regional interpretation of water quality monitoring data. Water Resources Research. 33:2781–2798

Smith, T.E., A.E. Laursen, and J.R. Deacon, 2008. Nitrogen attenuation in the Connecticut River, northeastern USA; a comparison of mass balance and N_2 production modeling approaches. Biogeochemistry 87, 311–323

U.S. Environmental Protection Agency, 2021a. Hydrological Simulation Program – FORTRAN (HSPF). https://19january2021snapshot.epa.gov/ceam/hydrological-simulation-program-fortran-hspf_.html. Accessed 13 August 2026.

U.S. Environmental Protection Agency, 2021b. "EQUATESv1.0: Emissions, WRF/MCIP, CMAQv5.3.2 Data -- 2002-2019 US_12km and HEMI_108km". UNC Dataverse, V5. https://doi.org/10.15139/S3/F2KJSK. Accessed 17 December 2025.

U.S. Environmental Protection Agency, 2025a, CMAQ—The community multiscale air quality modeling system: U.S. Environmental Protection Agency website. https://www.epa.gov/cmaq/. Accessed 17 December 2025.

U.S. Environmental Protection Agency, 2025b. Dasymetric Toolbox, Dasymetric Mapping. U.S. Environmental Protection Agency. https://www.epa.gov/enviroatlas/dasymetric-toolbox. Accessed 30 January 2026.

U.S. Geological Survey, 2025. USGS Water Data for the Nation: U.S. Geological Survey National Water Information System database. https://doi.org/10.5066/F7P55KJN. Accessed 17 December 2025.

U.S. Geological Survey, Earth Resources Observation and Science (EROS) Center, 2018. National Land Cover Database. https://www.usgs.gov/centers/eros/science/national-land-cover-database. Accessed 9 September 2023.

Wieczorek, M.E., S.E. Jackson, G.E. Schwarz, A.J. Sekellick, and L.E. Staub, 2018. Select Attributes for NHDPlus Version 2.1 Reach Catchments and Modified Network Routed Upstream Watersheds for the Conterminous United States (ver. 5.0, June 2025). U.S. Geological Survey data release. U.S. Geological Survey data release. https://doi.org/10.5066/F7765D7V. Accessed 17 December 2025.

Wieczorek, M. E., S. E. Jackson, G. E. Schwarz, A. J. Sekellick and L. E. Staub, 2022a. Attributes for Nhdplus Version 2.1 Catchments and Modified Routing of Upstream Watersheds for the Conterminous United States: National Land Cover Database 2019 Versions for the Years 2001, 2004, 2006, 2008, 2011, 2013, 2016, and 2019. U.S. Geological Survey Data Release. https://www.sciencebase.gov/catalog/item/63935b30d34e0de3a1efe082. Accessed 17 December 2025.

Wieczorek, M.E., , R.P. Signell, G.J. McCabe, D.M. Wolock., 2022b. USGS monthly water balance model inputs and outputs for the conterminous United States, 1895-2020, based on ClimGrid data. U.S. Geological Survey data release. https://doi.org/10.5066/P9JTV1T6. Accessed 11 December 2023.

Wieczorek, M.E., R.P. Signell, G.J. McCabe, D.M. Wolock., and P.A. Norton, 2024. USGS monthly water balance model inputs and outputs for the conterminous United States, 1895-2020, based on ClimGrid data. U.S. Geological Survey data release. https://doi.org/10.5066/P9QCLGKM. Accessed 17 December 2025.

Wolock, David M., 1997. STATSGO soil characteristics for the conterminous United States, U.S. Geological Survey Open-File Report 97-656.

Seasonal Estimates of Instream Nitrogen & Phosphorus Loads from New England Watersheds Discharging to Long Island Sound for the years 2000-2020

By Richard B. Moore, Richard A. Smith, Laura Hayes, Jennifer Stanton, and Craig Brown

SUPPLEMENT – Model Residuals

Nitrogen Model Residuals

Average seasonal residuals for nitrogen are generally relatively well distributed (figure S1). There are, however, groups of higher predictions (negative residuals) in winter in Connecticut, and groups of lower predictions (positive residuals) in northern sites in New Hampshire and Vermont during the spring. Both groups of residuals indicate that increases in model accuracy could be attained by developing and incorporating predictors that better define winter and spring conditions that relate to nitrogen sources and delivery. There are, however, no temporal patterns or trends in the nitrogen residuals.

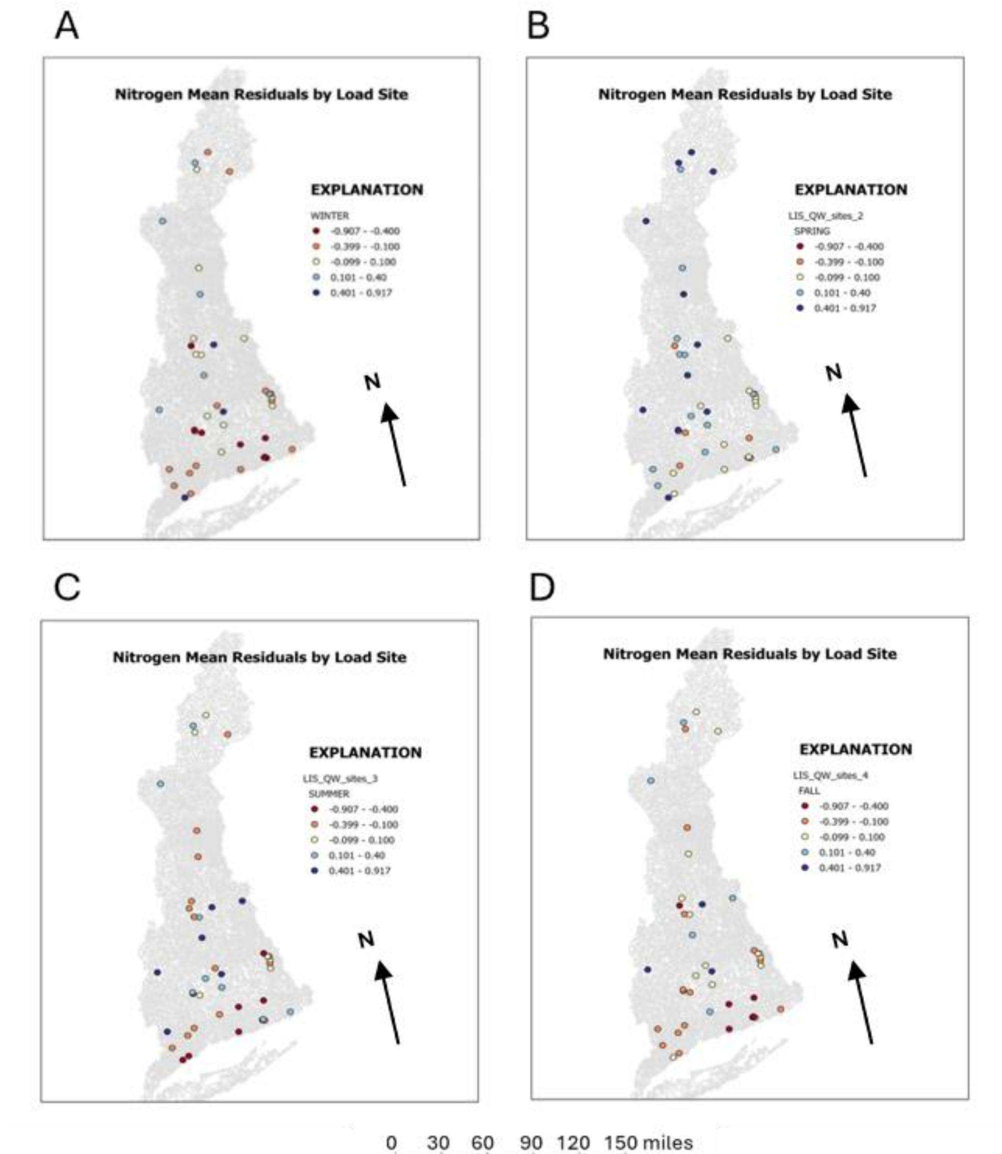

Figure S1. Average seasonal residuals, for the Long Island Sound dynamic nitrogen SPARROW Model for A) winter; B) spring; C) summer; and D) fall.

Phosphorus Model Residuals

Average seasonal residuals for phosphorous are generally relatively well distributed (figure S2). There are, however, groups of higher predictions (negative residuals) in summer and fall in the three most northern sites (Moose River at Victory VT, Passumpsic River at Passumpsic VT, and Ayres Brook at Randolph VT), and in the northern-most site (Moose River at Victory VT) for all 4 seasons. There are no temporal patterns or trends in the phosphorus residuals.

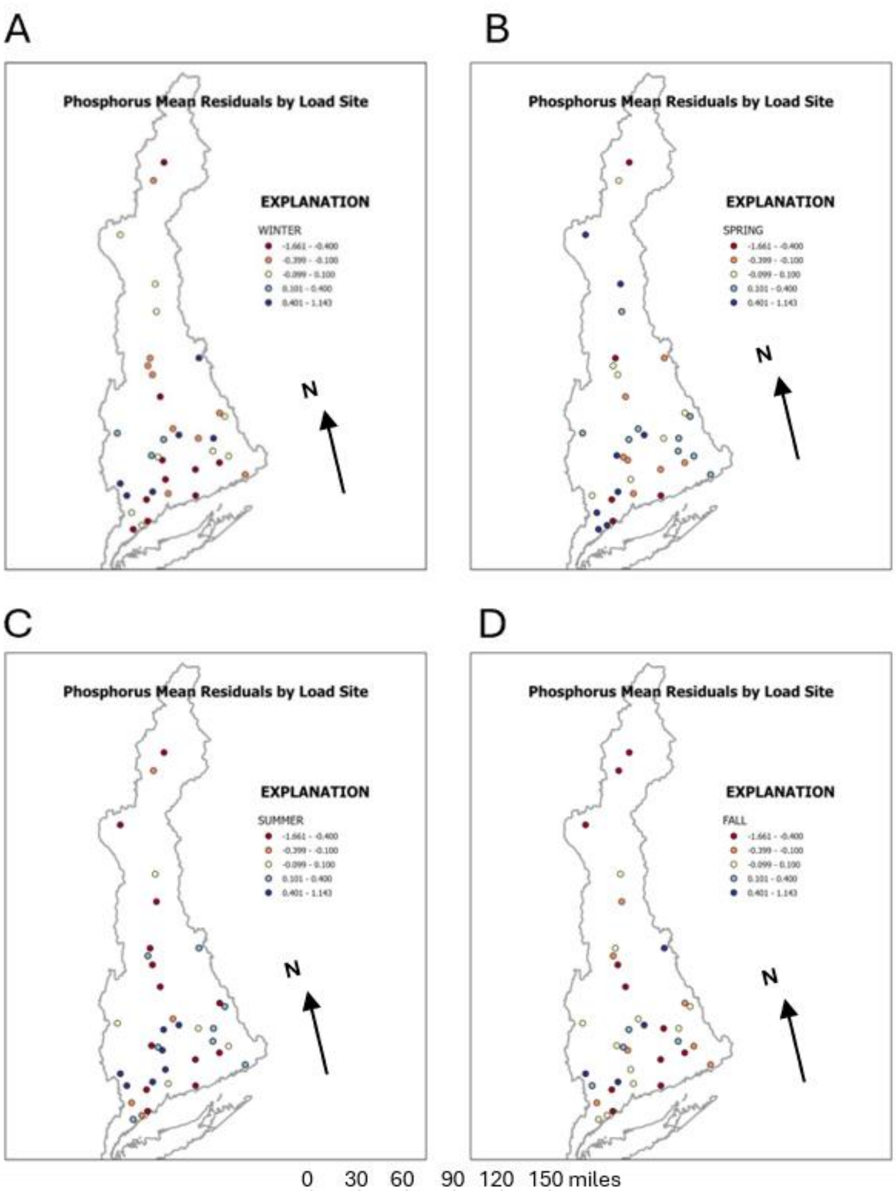

Figure S2. Phosphorous model residuals, averaged by season, for the Long Island Sound dynamic seasonal Phosphorous SPARROW Model. Upper left is average residual for winter; upper right is average residual for spring; lower left is average residual for summer; and lower right is average residual for fall.

REFERENCES

Hirsch, R.M., D.L. Moyer, and S.A. Archfield, 2010. Weighted Regressions on Time, Discharge, and Season (WRTDS), With an Application to Chesapeake Bay River Inputs. Journal of the American Water Resources Association 46(5):857-880.

Lee, C.J., R.M. Hirsch, G.E. Schwarz, D.J. Holtschlag, S.D. Preston, C.J. Crawford, and A.V. Vecchia, 2016. An evaluation of methods for estimating decadal stream loads, Journal of Hydrology, Volume 542, 2016, p. 185-203

Moore, Richard B., Stanton, Jennifer S., and Hayes, Laura, 2026, Long Island Sound nitrogen and phosphorus SPARROW models, including model inputs and outputs, 2000-2020: U.S. Geological Survey data release, https://doi.org/10.5066/P13MNQCH. Accessed 24 July 2026.

Schwarz, G.E., Hoos, A.B., Alexander, R.B., Smith, R.A., 2006. The SPARROW Surface Water-Quality Model—Theory, Applications and User Documentation. U.S. Geological Survey Techniques and Methods, Book 6, Chapter B3, The SPARROW Surface Water-Quality Model—Theory, application and user documentation. Online only.

U.S. Geological Survey, 2025. USGS Water Data for the Nation: U.S. Geological Survey National Water Information System database. https://doi.org/10.5066/F7P55KJN. Accessed 17 December 2025.